ELECTRIC MAINS

AND

DISTRIBUTING SYSTEMS

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PREFACE TO SECOND EDITION.

THE reception accorded to the First Edition was gratifying evidence of the useful purpose which the Authors hoped the book would serve. The issue was soon out of print, and, unfortunately, owing to the difficulties of the war period, a Second Edition could not immediately be produced. The present volume, while retaining the main features of the original, has been thoroughly revised and considerably amplified. The suggestions of actual users of the book, and the kind advice of many friends, have been followed wherever possible. In this connection particular reference might be made to the arithmetical examples of the application of each one of the formulæ for mains calculations in Part I. It is hoped that this feature will materially enhance its value both to the mains' engineer and general student.

In the description of the theory and operation of modern cables, especially the H.T. and E.H.T. varieties, the Authors have not hesitated to state their views, based on experience, even where these may appear somewhat unorthodox. One of the Continental reviewers of the First Edition remarked that the requirements of the actual live engineer had never been lost sight of, and, if the present volume further strengthens this criticism, the authors will feel that its chief aim has been attained.

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PART I.

CHAPTER I.

PRINCIPLES OF NETWORK DESIGN.

General Problem of the Design of Cable Systems.

The lay-out and calculation of a distribution system to supply a large area is, in this country at least, usually considered to be a problem best solved by methods based on experience.

The tendency to rely on empirical rules is, no doubt, due to the feeling that the data at the disposal of the engineer are too uncertain to justify any attempt at an exact mathematical solution.

This inherent uncertainty is probably responsible for the safe but unenterprising rule frequently quoted in earlier days, to put down "plenty of copper" to allow for unforeseen developments. But it is somewhat of a reproach to distributing engineers when the elements of a network are not considered as carefully as the members of a steel bridge truss, although some of the data for the latter suffer from a corresponding lack of definiteness. In the present work we hope to show the value of a few simple rules and formulæ in ensuring that the copper actually laid down is correctly and efficiently used.

Historically the small low-tension system came first, but when once the principles of its design have been grasped it is easy to pass on to the consideration of the largest modern high pressure transmission and distribution schemes. We propose, therefore, to begin by giving a short survey of the general problem of a low-tension direct current two-wire system with inter-connected network and feeders.

Low Tension Network.   Essential Conditions.

One of the chief objections raised by those engineers, who view theoretical design with disfavour, is this.   They argue that, though it may be possible to calculate the sizes of the mains when the undertaking is started, or at any given stage in its development, the character and amount of the loads in different districts may vary to such an extent in a year or two as practically to nullify the results obtained by calculation.

Some writers on the subject have not hesitated to say that the most that can be done is to choose the dimensions of the distributing mains with a margin liberal enough for any future loads, and to make provision for increasing the sections of the feeders or adding to their number as the necessity arises.

Even within these limitations there are some cardinal principles which must be more or less consciously applied by the designer in dealing with a new network.   Again, it is frequently important in the routine of the station management to know what is happening at different po nts of an existing network, and for this purpose the same principles must be applied.

The first task of the designer is the preparation of a plan of the distributing mains in the district.   For underground (but not necessarily for overhead) distribution the outlines of the network follow the plan of the principal streets.

Starting with this skeleton network the unknown quantities to be determined are the *sizes of the distributor cables, and the number, size, and position of the feeders , in order to ensure that the pressure at any consumer's terminals may not vary beyond certain limits.*   Where incandescent lamps preponderate this condition is a *sine qua non,* but where the current is used entirely for motive power the same importance is not attached to pressure variations, and the calculation of the cable sizes may rest on a different basis.   There is one criterion affecting the reliability of the supply to which reference has constantly to be made—that is, to keep the maximum current densities low enough to prevent undue heating of the cables.   Another principle not to be overlooked is that of efficiency.   This implies the determination of the sizes of the conductors to satisfy the technical requirements just given while keeping the capital cost and annual charges against the system at a minimum.   Bearing in mind these three essentials of (1)

pressure regulation, (2) temperature rise, (3) efficiency, the development of the design would be somewhat as follows.

Estimation of the Loads.

The consumers' loads must in the first instance be estimated. They vary in amount with the industrial character of the town, but from the experience now available in all kinds of towns the number of consumers and their demands can be assessed with considerable accuracy in any street.

Having considered the class of premises and the probable number of lamps, motors, and other appliances to be connected ultimately, the best plan is to express this as a uniformly distributed load in amperes per yard of main. In reckoning the load in amperes for a lighting system the 8 c.p. 28 watt lamp was formerly adopted as the unit This allowed a substantial margin of copper, due to the increasing efficiency of metallic filament lamps, and for a network being laid down to-day due consideration should be given to this point. It is interesting to note that in course of time the changes in methods of distribution, such as the introduction of the three-wire system, doubling the pressure, and the use of high efficiency lamps, have virtually increased the capacity of existing mains many times, thus concealing errors due to want of foresight in the original design and postponing the period when the addition of copper becomes imperative.

Besides the uniformly distributed load thus estimated, allowance will have to be made at the proper points for specially heavy loads, such as hotels, factories, office blocks, &c. The figures so obtained are, moreover, liable to alteration at a later date by the erection of a business block, hotel or factory displacing old property. The cross-sections will not have been calculated so closely however as to be incapable of dealing with extra demands of this kind, and, as will be shown later, there are various ways of meeting this difficulty.

Position of Central Station and Feeding Points.

When the positions and probable values of the loads are indicated on the map of the district the next logical step is to choose a site for the central station. This should be as nearly as possible at the centre of the mean position of all the loads considered as masses. Unfortunately a site to satisfy this

condition would be near the centre of the town or district, and too expensive. The engineer has, besides, other considerations to weigh, which do not concern us here, and for our purpose we may assume that its position is fixed as favourably as possible for the load centres.

The outlines of the network and the position of the central station being given, the important question arises of how many feeders to employ, and where to connect them, so that the pressure may be maintained within the prescribed limits. To satisfy this requirement alone an endless number of arrangements could be made, but there is one which is theoretically the best, *i.e.*, when the total cost of the network and feeders together is a minimum. Obviously such a minimum is possible, for one broad alternative is to have numerous feeders with the network cables comparatively small, while the other is to have fewer feeders and the distributors much heavier. The fact that distributors and feeders are run at different current densities has also to be borne in mind.

It must be pointed out that minimum cost is not necessarily the same thing as minimum weight of copper, for to the latter has to be added the cost of its manufacture into cable and that of erection or laying. The mathematical determination of the number and position of feeders to give the most economical result (not merely the minimum weight of copper) is possible in certain simple cases, of which illustrations will be given later, but there is no general solution that would be applicable to ordinary working conditions. For the preliminary project all that can be premised is that the *feeders should be run by the shortest routes to the natural load centres of the areas they are intended to supply.* Owing to the lack of precise rules the initial positions may have to be adjusted by the information obtained from a further study of the network.

The question of regulating the pressure at the feeding points simply and effectively has also an important influence on the selection of their positions. If it is impossible to have all the feeders of approximately the same length, it is advisable to arrange that they fall into groups according to length so that each group may be connected to a separate 'bus bar run at a voltage giving the proper value at the feeding point. In effect the procedure has to be one of trial and error, with the ultimate object of reducing the capital expenditure to a minimum.

The same principles are applicable to both the primary and secondary networks of high-tension systems with sub-stations.

Determination of Cross-sections of Distributors and Feeders.

The next step in the design is to ascertain the total load and the drop in each distributor, with the feeders in their assumed positions. A distributor fed from one end only presents no difficulty, as its total load is at once given by adding all the consumers' loads. For distributors connecting two feeders it may be taken as a first approximation that each of the latter will supply current to a point midway to the next. This is called the " cutting point," as it is there that the current in the distributor changes its direction. It is there also that the drop in voltage is greatest. By adding all the loads in the cables between the cutting points and the feeding point the total current in each feeder is determined at once, and from Kelvin's law of the most economical current density their sizes can be calculated. In dealing with the distributors the one governing condition is to make the maximum drop at full load between the feeder and the cutting point less than the amount permitted by the Board of Trade. The cable section employed is not that calculated, but preferably the standard size next larger

After having determined the sizes of all the distributors and feeders to satisfy the technical and economic conditions it is necessary to compare the working current densities with the maximum values which are permissible without causing too great a rise in temperature. Although these vary somewhat according to the nature of the dielectric, mode of laying, &c., the figures given in the Inst E E. Wiring Rules should not be exceeded. When all the cross-sections have been checked and altered where necessary, the result is a complete network of distributors and feeders each of which is approximately dimensioned. The next series of operations, a refinement which many engineers dispense with, is to regard the network with its loads as given, and to ascertain the actual voltage at every important point and the full-load current in every cable. This is a tedious but not really a difficult matter. Several methods are available, all of which finally result in obtaining n simultaneous equations, if there are n meshes in the network. The solution of these gives the voltages at every point, from which the currents can be calculated or

vice versa. The results may diverge considerably from the assumptions on which the cross-sections were tentatively based, and alterations in the latter may have to be made. Theoretically any change of this kind will influence the whole system, but as the effect is negligible at points remote from the feeders immediately concerned it is unnecessary to go through the tedious process of re-determining the complete current and voltage distribution. (Teichmüller, *E.T.Z.*, 1901, No. 11.)

The basis of all the calculations has hitherto been taken to be the maximum possible load as far as it can be foretold. It is well known, however, that the actual maximum demand may only be 30 to 70 per cent. of this, especially if the diversity factor also be taken into account. Thus the loads originally calculated for the cables and consequently their cross-sections can be diminished by a ratio depending on the class of consumer and the character of the town. This ratio will obviously be different in the industrial and residential districts.

Although the supply to the whole of an authorised area may be provided for in the manner just described the complete network need not be laid down at once, for in very few cases would the capital expenditure be justified. It is more usual to let it gradually be evolved in accordance with the demands for current that arise in different districts, or a sufficient number of spare ducts or cableways may be laid into which additional copper can be drawn at a later date. It is advisable, however, to work to a scheme for the entire network, so that as it develops naturally each part may be correctly proportioned for its ultimate duty. Otherwise the total cost is likely to be excessive or the voltage regulation unsatisfactory. It will be apparent from the general review of the methods adopted even before going into details that they are not susceptible of mathematical treatment to give a single best solution. When such exists it has to be found by a process of trial and error. In other words any network can be completely analysed by the application of Ohm's and Kirchoff's laws but there are no *simple* rules for constructing a network synthetically. Thus the designing is possibly as much of an art as a science, and experience may be able to hit upon an arrangement as good as that obtained from a laborious series of arithmetical operations, but a verification by the methods indicated is always desirable.

CHAPTER II.

THE CALCULATION OF DISTRIBUTORS.

Network Loads and Currents. Limit of Voltage Variation in Distributors.

In discussing the general problem of interconnected conductors supplying consuming devices, the latter may be considered as resistances with or without back E.M.F., and can be completely dealt with by Kirchoff's laws. It is simpler, however, to take the current passing through a lamp or motor instead of its resistance, and to use other methods. The principles discussed here apply only to continuous currents or to non-inductive alternating circuits. The modifying effects of induction and capacity will be dealt with subsequently. Fortunately the voltage across the mains can be assumed to be practically constant at any point of the longest distributor, this being due to the very condition intended to be safeguarded by the calculations, viz., the restriction of the pressure variation within the limits of $2\frac{1}{2}$ to 3 per cent. The B.O.T. permits a total variation of 4 per cent., but some part of this should be reserved for loss in service wires and apparatus. Thus the actual voltage at the furthest service box must not differ more than 3 per cent. from the declared value. The load currents for the various appliances being found by dividing each load by the declared voltage would not be subject to an error of more than 3 per cent. Hence also the drop obtained by assuming a constant voltage along the whole length of the distributor would be correct within a small percentage.

Feeder or Distributor Supplying Single Load.

The resistance R of a conductor, fed from one end, of length L and cross-section S is expressed by the formula $R = \dfrac{L}{KS}$ ohms, where K is a constant depending on the specific conductivity of the material in the conductor.

When this is of copper, and L is measured in yards and S in square inches (the most generally used British units), the value of the constant K is very approximately 40,000 at 20°C. The drop of pressure v, in the conductor carrying the current C is, $v = CR$. Substituting for R as above, this expression becomes

$$v = \frac{CL}{KS}, \text{ or } S = \frac{CL}{Kv},$$

the fundamental formula in calculating cross-sections of feeders and distributors supplying single loads   The following modification of the formula is often used when the load supplied is stated in kilowatts instead of amperes, and the drop is specified as a percentage p of the pressure V, at the point where the load is supplied.

For a load of W kilowatts

$$C = \frac{W \times 1,000}{V} \text{ amps,}$$

and the drop $v = pV$ for the complete circuit—forward and return wires, the single length of each being L.

Thus, for the circuit, $S = \dfrac{2CL}{Kv}$ becomes

$$S = \frac{2 \times 1,000 \text{ WL}}{KpV^2}.$$

When several loads C_1, C_2, C_3, &c., are supplied from the same distributor at distances L_1, L_2, L_3, &c., from the feeding point, the drop to the farthest in each wire is

$$v = \frac{C_1 L_1}{KS} + \frac{C_2 L_2}{KS} + \frac{C_2 L_3}{KS} + \&c. = \sum_1^n \frac{C_n L_n}{KS},$$

and

$$S = \frac{1}{Kv} \cdot \sum_1^{\ell_n} C_n L_n.$$

Pressure Drop in Uniformly Loaded Distributor Fed at One End.

The case of a distributor fed at one end only is frequently met with in the outlying parts of a network, and it occurs again

when there is an assumed cutting point in the main connecting two feeders. It is often advantageous to treat such a distributor as if it were uniformly loaded, and the voltage drop at the farthest point is determined as follows :—

c_n=current taken by any consumer, and

r_n=the resistance between any two consumers (Fig. 1).

The total drop

$$v = c_1 r_1 + c_2(r_1 + r_2) + c_3(r_1 + r_2 + r_3) \ldots + c_n(r_1 \ldots r_n),$$

which is simply the sum of the drops due to each load reckoned from the point of supply F, or what may be called the moments of the currents about that point. If the loads are all equal and equidistant, on a conductor of constant cross-section, $v = cr + c . 2r + c . 3r + \ldots c . nr$, and the total drop is the sum of this arithmetical progression,

$$v = cr\frac{n}{2}(1+n),$$

or when n is large, $$v = cr\frac{n^2}{2}.$$
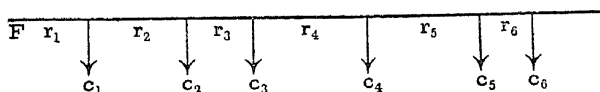
Fig. 1.

If the current is taken off the mains fairly regularly at short intervals, we can treat the load as equivalent to an uniform one of C_0 amperes per unit length. If the length is L the total load is

$$C_0 L = nc \text{ and } c = \frac{C_0 L}{n}.$$

Further, if the main be of uniform cross-section and total resistance R, for any of the n elements,

$$r = \frac{R}{n}, \text{ and } v = cr . \frac{n^2}{2}$$

becomes $$v = \frac{C_0 L}{n} . \frac{R}{n} . \frac{n^2}{2} = \tfrac{1}{2}C_0 . L.R.$$

Since C_0L is the total current the drop at the far end is that due to the whole load acting at half the distance from F. If the distributor is considered as a cantilever and the currents replaced by weights the analogy between the drop and the bending moment will be at once apparent. The similarity of the two problems is useful in some cases which have to be dealt with graphically, but with non-inductive loads graphic methods have little advantage over the arithmetical, except where the object aimed at is to find a minimum value so that a certain best result is achieved. In dealing with alternating currents graphic methods are in many cases preferable, owing to the complexity of the algebraical expressions.

With an uniformly loaded distributor $v = \frac{1}{2} \cdot C_0 \cdot LR$ becomes, by substituting

$$R = \frac{L}{SK}$$

$$v = \frac{1}{2} \cdot \frac{C_0L^2}{SK}$$

or

$$S = \frac{1}{2} \frac{C_0L^2}{vK},$$

which enables the cross-section to be calculated. In determining cross-sections in distributors on a public supply system the maximum drop reckoning from the feeding point may be taken as 3 per cent. of the declared pressure V, half this quantity applying to each of the two wires. If, in addition, to the uniform load C_0 in amperes per yard run, there are some exceptionally large consumers, or singly-fed side streets whose loads are C_1, C_2, C_3, &c., at distances l_1, l_2, l_3, the total drop is then

$$v = \frac{1}{2} \cdot \frac{C_0L^2}{SK} + \frac{C_1l_1 + C_2l_2 + C_3l_3 \ldots . C_nl_n}{SK}$$

$$= \frac{1}{2} \frac{C_0L^2}{SK} + \Sigma_1^n \frac{C_nl_n}{SK}$$

and

$$S = \frac{1}{vK} \cdot (\tfrac{1}{2}C_0L^2 + \Sigma_1^n C_nl_n).$$

These formulæ refer only to one conductor of a two-wire main, and if the drop is v for the positive and negative together, or the total drop in the circuit, the formulæ become

$$v = \frac{C_0 L^2}{SK} \text{ and } S = \frac{C_0 L^2}{vK}, \; S = \frac{2}{vK} \cdot \Sigma_1^n C_n L_n, \text{ &c.}$$

It must be carefully noted in all these formulæ that L is the distance from the feeding point to the end of the distributor.

Drop and Cross-section of Distributor Fed at Both Ends.

When the distributor joins two feeding points or forms an inter-connector of the network so that it is fed from both ends (Fig. 2) it is obvious at once that, with the assumed simplification of uniform loading, the cutting point P is midway between F_1 and F_2, and is the point of lowest voltage, if the pressures

F_1 P F_2

FIG. 2.

are the same at each. Then $F_1 P$ and $F_2 P$ can be considered as conductors fed from one end only. If L is the distance $F_1 F_2$ then

$$F_1 P \text{ is } \tfrac{1}{2}L \text{ and } v = \tfrac{1}{2}\frac{C_0 F_1 P^2}{SK} = \tfrac{1}{8}\frac{C_0 L^2}{SK} \text{ and } S = \tfrac{1}{8}\frac{C_0 L^2}{vK}.$$

Thus the maximum drop with the same cross-section and length of main fed from its two ends is only one quarter of that of a main fed at one end, or it could carry four times the load with the same drop. It does not follow, however, that these advantages could be realised, as the cross-section might fail to conform to the criterion of safe current density. The value of this near to the single feeding point would be

$$C_0 L \div \tfrac{1}{2}\frac{C_0 L^2}{vK} = \frac{2vK}{L} \text{ amperes per square inch.}$$

With two feeders the value near the feeding point would be

$$\tfrac{1}{2}C_0 L \div \tfrac{1}{8}\frac{C_0 L^2}{vK} = \frac{4vK}{L}.$$

Thus the current density would be doubled, and if already at the maximum it would not be possible to have the area of the main one quarter of its former value when fed at each end. But if the value of the drop is made v_1, one-half what it was before, or if the conductor is made of half instead of quarter the section :—

$$S = \tfrac{1}{8}\frac{C_0 L^2}{v_1 K} = \tfrac{1}{4}\frac{C_0 L^2}{v K}, \text{ since } v_1 = \tfrac{1}{2}v,$$

and current density

$$= \tfrac{1}{2}C_0 L \div \tfrac{1}{4}\frac{C_0 L^2}{v K} = 2\frac{K v}{L},$$

which is the same value as for the main fed at one end, and assumed to be running at its maximum current density before the second feeder was added. For short lengths of main the temperature rise and not the voltage drop may be the dominating factor in imposing a limit to the current density. Thus, in a uniformly loaded two wire circuit, if $v = 5$ volts (or $2\tfrac{1}{2}$ per cent. of 200 volts) and $L = 100$ yds. (or 200 forward and return),

$$\text{Max}^{\text{m}} \text{ current density} = \frac{2K v}{L} = \frac{2 \times 40{,}000 \times 5}{200}$$

$$= 2{,}000 \text{ amperes per square inch.}$$

This being inadmissible the voltage drop would have to be taken about $1\tfrac{1}{4}$ per cent. instead of $2\tfrac{1}{2}$ per cent. in that length of main, which would bring the value to approximately 1,000 amperes per square inch—a safe figure for the usual size of distributors.

Examples of the Use of the Formulæ for Distributors.

1. On a two-wire 250 volt system a singly fed distributor 400 yards long supplies a consumer taking a load W of 30 kw. at its extremity, and it is required to find its cross-section, when the drop must not exceed 3 per cent. of the declared pressure V between the conductors.

Current $C = \dfrac{W \times 1{,}000}{V}$ amps. $= \dfrac{30 \times 1{,}000}{250} = 120$ amps.

Drop $\qquad v = pV = 0.03 \times 250 = 7.5$ volts.

$$S = \frac{2CL}{Kv} \text{ where L is the length of one wire or 400 yds..}$$

$$S = \frac{2 \times 120 \times 400}{40,000 \times 7.5} = 0.32 \text{ sq. inches.}$$

Alternatively if the cross-section S of the main is given as 0·32 its resistance

$$R = 2\frac{L}{KS} = \frac{2 \times 400}{40,000 \times 0.32} = 0.0625 \text{ ohms.}$$

The drop $\qquad v = CR = 120 \times 0.0625 = 7.5$ volts.
The current density

$$= \frac{C}{S} = \frac{120}{0.32} = 375 \text{ amps per sq. in, which is well}$$

within the safe limit   Using the formula

$$S = \frac{2 \times 1,000 \cdot W \cdot L}{K \cdot p \cdot V^2} \text{ where W is in kilowatts.}$$

$$S = \frac{2 \times 1,000 \times 30 \times 400}{40,000 \times 0.03 \times 250 \times 250} = 0.32 \text{ sq. in., as before.}$$

This is the most convenient formula when the load is stated in kw., and the cross-section only is required.

2. A number of different loads C_n are supplied from a distributor fed at one end at distances L_n from the feeding point as shown :—

Loads (C_n).	Distances from Feed point (L_n).	$C_n \times L_n$.
C_1 12 amperes	20 yards	240
C_2 18 ,,	100 ,,	1,800
C_3 15 ,,	140 ,,	2,100
C_4 8 ,,	200 ,,	1,600
C_5 25 ,,	230 ,,	5,750
C_6 20 ,,	290 ,,	5,800
C_7 10 ,,	340 ,,	3,400
C_8 7 ,,	400 ,,	2,800
$115 = \Sigma_1^n C_n$		$23,490 = \Sigma_1^n C_n L_n$

The cross-section is found from the formula

$$S = \frac{1}{Kv} \cdot \Sigma_1^n C_n L_n \text{ (for one conductor),}$$

or $S = \dfrac{2}{Kv} \cdot \Sigma_1^n C_n L_n$ for the two conductors; v as before is
3 per cent. of 250 volts $= 7·5$ volts,

and $S = \dfrac{2 \times 23{,}490}{40{,}000 \times 7·5} = \dfrac{46\,980}{300{,}000} = 0·1566$ sq. in.

We shall now ascertain what error would be introduced by taking an equivalent uniform load instead of the individual loads at the irregular distances shown.   The total load $\Sigma_1^n C_n$ is 115 amps. and if this is taken off uniformly it amounts to $\dfrac{115}{400} = 0·28$ amps. per yard run (approx.), since the length of the distributor is 400 yards.

We use the formula $S = \dfrac{C_0 L^2}{Kv}$ in which C_0 is the load in amps. per yard run.

$$S = \frac{C_0 L^2}{Kv} = \frac{0·28 \times 400 \times 400}{40{,}000 \times 7·5} = 0·15 \text{ sq. in (approx.).}$$

An alternative method is to remember that a uniform loading produces the same drop as the total load collected at the middle of the distributor; thus we find from the general formula $S = 2 \cdot \dfrac{CL}{Kv}$ (where C is the total load),

$$S = 2\frac{C \times ·5L}{Kv} = \frac{2 \times 115 \times 0·5 \times 400}{40{,}000 \times 7·5} = 0·153.$$

The current density in the portion nearest the feed point

$$= \frac{C}{S} = \frac{115}{0·153} = 750 \text{ amps. per sq. in.}$$

It will be recognised at once that treating this set of loads as equivalent to a uniform supply per yard run causes no appreciable error.   The denser the load the less the error in replacing it by a uniform rating.

Suppose now there are two side streets fed from this main, one at 150 yds. distance with 80 amps., and the other at 200 yds. with 65 amps., these loads must be considered separately, as they are so much greater than the average, and could not be included in the uniform rating

The formula

$$S = \frac{2}{Kv}\left(\tfrac{1}{2}C_0 L^2 + \Sigma_1^n C_n l_n\right),$$

or $S = \dfrac{C_0 L^2}{Kv} + \dfrac{2}{Kv} \cdot \Sigma_1^n C_n l_n$ is then applicable.

The first part has already been found to be 0·15 sq in.
The second part

$$= \frac{2 \times (80 \times 150 + 65 \times 200)}{40,000 \times 7\cdot 5} = 0\ 166 \text{ sq. in.}$$

The correct cross-section is, therefore, 0·15 + 0·166 = 0·316 sq. in. Maximum current density

$$= \frac{115 + 80 + 65}{0\cdot 316} = 820 \text{ amps. per sq. in}$$

3. In Example (2) if the conditions are altered so that the main is now fed from both ends instead of one, the cross-section is given by the formula

$$S = 2\left(\tfrac{1}{8} \cdot \frac{C_0 L^2}{Kv}\right).$$

The drop v is to be the same, viz., 7·5 volts, and thus

$$S = \tfrac{1}{4} \cdot \frac{0\cdot 28 \times 400 \times 400}{40,000 \times 7\cdot 5} = 0\cdot 038 \text{ sq. in ,}$$

or one quarter of that of the singly fed distributor. Of the total current, 115 amps., half is derived from each feeder, and thus the maximum current density is

$$\frac{C}{S} = \frac{57\cdot 5}{0\cdot 038} = 1,500 \text{ amps. per sq. in.}$$

This figure is still safe for the cross-section considered, but for heavier sections it might be dangerous.

4. If the distributor 400 yds. long forms part of a three-wire system at 2×250 volts, the cross-section, for the same percentage drop, is found as follows, when the single load of 30 kw. is supplied at one end, and is connected up so as to be equally balanced on the positive and negative sides. Neglecting the third wire we then have the equivalent of a two-wire circuit at 500 volts :—

$$S = \frac{2 \times 1{,}000 \cdot W \cdot L}{K \, p \, V^2} = \frac{2{,}000 \times 30 \times 400}{40{,}000 \times 0 \cdot 03 \times 500 \times 500} = 0 \cdot 08 \text{ sq. in.}$$

The cross-section of the middle wire is half this, or 0·04 sq. in

$$\text{Current } C = \frac{W \times 1{,}000}{V} \text{ amps.} = \frac{30 \times 1{,}000}{500} = 60 \text{ amps.}$$

in each of the outers.

$$\text{Current density} = \frac{C}{S} = \frac{60}{0 \cdot 08} = 750 \text{ amps. per sq. in.}$$

When the loads making up 115 amps. are supplied by this three-wire main the equivalent uniform loading would, of course, be only half its value on the two-wire system, or 0·14 amp. per yard instead of 0·28.
Hence the cross-section

$$S = \frac{C_0 L^2}{K v} = \frac{0 \cdot 14 \times 400 \times 400}{40{,}000 \times 15} \text{ (as } v = p V = 0 \cdot 03 \times 500 = 15)$$

and $S = 0 \cdot 038$ sq. in.

It will be clear from these examples that the same saving in copper is effected by (*a*) feeding the main at both ends at 250 volts two-wire, or (*b*) using a singly fed distributor on a 2×250 volt three-wire circuit.

Corresponding to example (3), if the three-wire main is fed at both ends, the cross-section would be

$$S = \tfrac{1}{4} \cdot \frac{C_0 L^2}{K v} = \frac{0 \cdot 038}{4} = 0 \cdot 009 \text{ sq. in.}$$

Conditions of Economy in Copper, when the Drop is fixed.

The principle of securing an economy in copper is exemplified in the comparison of the cross-section of distributors fed at one or both ends respectively. A little con-

sideration will show that, under the conditions of a limiting drop, the area of the conductor should, theoretically, not be the same throughout, but that it should be stepped in accordance with the load at each point, to give the best economy

The law on which the stepping is based is derived as follows :—

FP_2 (Fig. 3) is a main fed from F supplying currents C_1 and C_2 at P_1 and P_2 so that the total drop to P_2 is V. The problem is to ascertain how this total drop is to be divided between the two lengths so that the volume of copper employed is a minimum.

The cross-section in $FP_1 = s_1 = \dfrac{(C_1 + C_2)l_1}{KV_1}$ (where V_1 is the drop from F to P_1),

$$\text{and in } P_1P_2 = s_2 = \frac{C_2 l_2}{K(V - V_1)}.$$
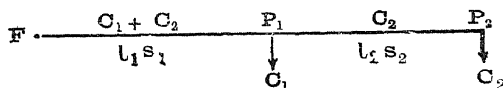
FIG. 3.

The volume of copper is $= M = l_1 s_1 + l_2 s_2$,

$$M = \frac{(C_1 + C_2)l_1^2}{KV_1} + \frac{C_2 l_2^2}{K(V - V_1)}$$

Differentiating with respect to the variable V_1, and equating to 0 to obtain the minimum value,

$$-\frac{(C_1 + C_2)l_1^2}{KV_1^2} + \frac{C_2 l_2^2}{K(V - V_1)^2} = 0,$$

$$\frac{V_1^2}{(V - V_1)^2} = \frac{l_1^2(C_1 + C_2)}{l_2^2 \cdot C_2},$$

$$\frac{V_1}{V - V_1} = \frac{l_1 \sqrt{C_1 + C_2}}{l_2 \sqrt{C_2}},$$

and as $\qquad V_1 = \dfrac{(C_1 + C_2)l_1}{s_1 K}$ and $V - V_1 = \dfrac{C_2 l_2}{s_2 K}$,

by substitution we obtain

$$\frac{s_1}{s_2} \quad \frac{\sqrt{C_1 + C_2}}{\sqrt{C_2}}.$$

In a similar way it can be shown, where the conductor is divided into any number of lengths carrying different currents, that, if s is the cross-section of any length and C the current in it, $\dfrac{C}{s^2}$ is constant. In dimensioning the conductor it follows that it should be stepped so that the cross-section of each part is proportional to the square root of the current it carries.

One case of some interest is that in which the current supplied by the distributor is tapped off at a uniform rate per yard run.

If FP (Fig. 4) is fed from F as before and is of length L the section s carrying current C,
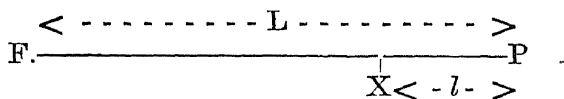
$$\text{Fig. 4.}$$

at any point X at distance l from P is given by $s/s_1 = \sqrt{C}/\sqrt{C_1}$ where s_1 and C_1 are the cross section and current at F. But $C = cl$ and $C_1 = cL$, where c is the load in amperes per yard run and $C = \dfrac{C_1}{L} \cdot l$, and $s = s_1 \dfrac{\sqrt{l}}{\sqrt{L}}$. The drop at any point X in an element dl at a distance l from P is

$$dv = -C \cdot \frac{dl}{Ks} = -\frac{C_1}{LKs} \cdot l \, dl.$$

Substituting $\qquad s = s_1 \dfrac{\sqrt{l}}{\sqrt{L}}, \quad \int dv = -\int \dfrac{C_1}{L^{\frac{1}{2}} Ks_1} \cdot l^{\frac{1}{2}} dl,$

and integrating $\qquad v = -\tfrac{2}{3} \cdot \dfrac{C_1}{L^{\frac{1}{2}} Ks_1} \cdot l^{\frac{3}{2}} + B$, where B is the constant of integration,

when $l = L$, $v = 0$ $\therefore$ $B = \tfrac{2}{3} \dfrac{C_1 L}{Ks_1}$,

and v at any point $\quad = \tfrac{2}{3} \dfrac{C_1}{Ks_1} \left(\dfrac{L^{\frac{3}{2}} - l^{\frac{3}{2}}}{L^{\frac{1}{2}}} \right)$,

when $l = 0$, $\qquad v_0 = \tfrac{2}{3} \dfrac{C_1 L}{Ks_1}$,

which is the total drop from F to P, and

$$s_1 = \tfrac{2}{3} \frac{C_1 L}{K v_0}$$

is the cross section at F.

When v_0 is stated, as is usual, the volume of copper is found thus :

$$\text{Volume } M = \int_0^L s \, . \, dl$$

$$= \int_0^L \tfrac{2}{3} \cdot \frac{C_1 L^{\frac{1}{2}}}{K v_0} \, l^{\frac{1}{2}} \, . \, dl, \text{ since } s = s_1 \frac{\sqrt{l}}{\sqrt{L}},$$

$$= \tfrac{4}{9} \cdot \frac{C_1 L^2}{K v_0},$$

or, as $C_1 = cL$, $$= \tfrac{4}{9} \cdot \frac{c L^3}{K v_0}.$$

From the former investigation of a conductor of uniform section, s_2, supplying a uniformly distributed load it was found that

$$s_2 = \tfrac{1}{2} \frac{c L^2}{K v_0},$$

and volume of copper is therefore

$$= \tfrac{1}{2} \frac{c L^3}{K v_0}.$$

Thus the saving in copper is only $\tfrac{1}{2} - \tfrac{4}{9}$, or about 11 per cent. If the load were distributed unequally and mostly at the far end the saving would be less, but if its " centre of gravity " lay nearer the feeding point than half way the saving would be proportionately more. If the length is so short that current density must be considered in selecting the size of conductor, some advantage lies with the stepped design just obtained.

Thus the current density at F, where the total current is cL, is

$$cL \div \tfrac{2}{3} \cdot \frac{c L^2}{K v_0} = \tfrac{3}{2} \cdot \frac{K v_0}{L},$$

whereas in the uniform conductor we have already found it to be $2K v_0/L$. Obviously this is due to the greater volume of

metal being placed near the feeding point, and graphically the relations of the two conductors are represented by the curve and dotted line in Fig. 5.

The curve is a parabola whose equation is

$$s = s_1 \frac{\sqrt{l}}{\sqrt{L}} \quad \text{(Fig. 5)}.$$

It may be observed that there is no saving in copper by tapering the conductor uniformly from F to P. At any point of such a conductor

$$C = C_1 \frac{l}{L}, \quad \text{and} \quad s = s_1 \frac{l}{L},$$

and, as before,

$$dv = -\frac{C}{Ks} \cdot dl,$$

$$dv = -\frac{C_1}{Ks_1} \cdot dl;$$

from which

$$v = \frac{C_1 L}{Ks_1} - \frac{C_1 l}{Ks_1}.$$
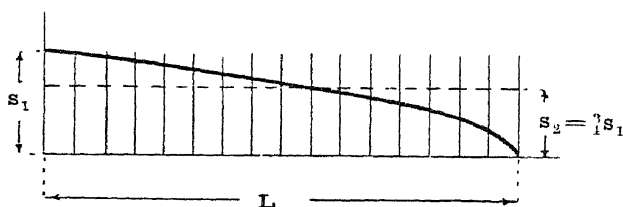
FIG. 5.

Cross-section at feeding point $= s_1 = \dfrac{C_1 L}{K v_0}$, varying down to 0, giving an average of $\frac{1}{2} \dfrac{C_1 L}{K v_0}$. With an uniform conductor the section was $\frac{1}{2} \dfrac{C_1 L}{K v_0}$; therefore the volume of copper is the same. Thus there is no advantage with the tapered conductor, except an equalising of the current density.

It is unnecessary to consider efficiency of running or minimising the $C^2 R$ losses, in dealing with distributors, as the one controlling condition is that the drop shall not exceed a certain maximum.

Example of Stepped Distributor.

4 A two wire, 250 volt main, 400 yds. long, is loaded as shown in Fig. 6 with 80 amps. at 200, 10 amps. at 300, and
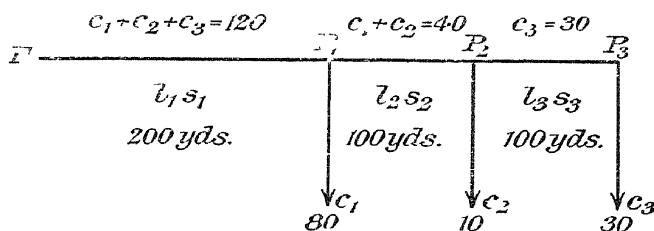
Fig. 6

30 amps. at 400 yds. from F. First express all the sections in terms of s_3

$$\text{Cross-section } s_2 = s_3 \frac{\sqrt{C_2 + C_3}}{\sqrt{C_3}} = s_3 \sqrt{\frac{40}{30}} = 1 \cdot 15 \, s_3$$

$$s_1 = s_3 \frac{\sqrt{C_1 + C_2 + C_3}}{\sqrt{C_3}} = s_3 \sqrt{\frac{120}{30}} = 2 s_3$$

As formerly, the total drop v is limited to 3 per cent. of 250 volts and $v = 7 \cdot 5$. In each of the three lengths the drop is $2\dfrac{CL}{Ks}$, C being the current each carries and s its own cross-section. The total drop is the sum of the three, therefore,

$$v = \frac{2 \cdot (C_1 + C_2 + C_3) l_1}{K s_1} + \frac{2(C_2 + C_3) l_2}{K s_2} + \frac{2 C_3 l_3}{K s_3}$$

$$= \frac{2}{K} \left(\frac{120 \times 200}{2 s_3} + \frac{40 \times 100}{1 \cdot 15 s_3} + \frac{30 \times 100}{s_3} \right)$$

$$= \frac{0 \cdot 924}{s_3} \quad \text{and} \quad s_3 = \frac{0 \cdot 924}{7 \cdot 5} = 0 \cdot 122 \text{ sq. in.}$$

$$s_2 = 1 \cdot 15 s_3 = 0 \cdot 140 \qquad s_1 = 2 s_3 = 0 \cdot 244,$$

or taking the nearest (larger) standard sizes the main would be laid as 200 yds. of 0·25, 100 yds. of 0·15, and 100 yds. of 0·125.

If the cross-section be supposed uniform it may be found from $s = \dfrac{2}{Kv} \cdot \Sigma_1^n C_n L_n$ as in example (2). Its value is 0·22, and as the nearest standard is also 0·25 there is a substantial saving in stepping the cross-sections.

The relative volumes and weights of copper are :—
Stepped main $200 \times 0.25 + 100 \times 0.15 + 100 \times 0.125 = 77.5$.
Uniform main $400 \times 0.25 = 100$, and the saving is $22\frac{1}{2}$ per cent. by using the former.

Limits of Law of Economy for Distributors.

The saving in copper, shown theoretically to be possible by varying the cross-section is not generally attainable. There are many objections to it, even if the steps are comparatively few. The primary difficulty is to provide suitable cross-sections from the standard sizes available, not to mention the expense of extra jointing.

Another difficulty arises if the distribution of current in the network is altered. It sometimes happens that a feeder has to be run to the middle point of a long distributor a considerable time after it is laid, in order to supply an unexpected demand for current. If, unfortunately, the two parts of it had originally been tapered down to small cross-sections at their cutting point they would be rendered entirely unsuitable for distributing the current from the new feeder, for it is axiomatic that the distributors meeting at a feeding point should have their aggregate cross-section at least equal to that of the feeder. In an interconnected network it is impossible to guarantee that large equalising currents may not flow in the distributors, as this depends on the variations of the loads and pressures in different districts. Were their cross-sections based on the law of minimum volume they would obviously possess little value as equalising mains. Nevertheless, in a district where there are long distributors terminating at a natural boundary and never likely to be fed from both ends, it might be advantageous to introduce several steps in the sizes. Where the system is in vogue of supplying distinct feeding areas from independent feeders, and consequently the distributors are not intended to be connected across at the cutting points except in emergencies, it might also be permissible to have graduated conductors. Except in rare instances the disadvantages would outweigh any saving to be obtained by adhering to the theoretical counsels of perfection implied in the formulæ.

One of the reasons for discussing this question somewhat fully is to show that, even where the voltage drop is fixed by the conditions of running, there is a definite law of minimum volume for distributing conductors.

CHAPTER III.

THE ASSOCIATION OF DISTRIBUTORS AND FEEDERS.

Simple Method of Treating Distributors and Feeders.

If the feeding points are given, the whole of the network can be split up into branches fed at one end only by the useful approximation of assuming the line of demarcation between any two feeder areas to be such that the current supplied to any installation is drawn from the feeder which has least intervening resistance. In other words, the " cutting points," through which the line of demarcation passes, lie midway electrically between each feeder.

Elasticity of Distributors.

A further assumption is obviously embodied in thus splitting up the network—*i.e.*, that the feeding points are all regulated to the same pressure, and consequently that there are no equalising currents flowing from one feeder area into another. The cross-sections of each of the branches can then be calculated from the formulæ already obtained, in all of which it was understood that the full load currents were being taken from the mains when the voltage drop was at its permitted maximum value. As such a state of things never occurs in practice, the amount of copper in the mains is more than is required for actual working, and the greater this margin is the more " elasticity " is the system said to possess. The elasticity fulfils the same function as special regulation, for it then becomes immaterial what fractions of the total demand may be in use simultaneously. The distributing mains, in contradistinction to feeders, must all be self-regulating by the possession of sufficient elasticity. It is unnecessary, however, to provide for a perfect elasticity which would be obtained if the switching of the *full* load on or off with constant feeding pressure did not cause a drop exceeding the limit. It is so rare to have all the connected load in use

at one time that the elasticity can be reduced to 40 or 50 per cent. of its perfect value without serious risk.   Various means are adopted for maintaining the elasticity without an excessive amount of copper, the principal one being to interconnect the network so that the lightly loaded parts may help those more heavily loaded.   Feeders are an example of inelastic conductors, as broadly considered the drop of pressure in them has no effect on the general network owing to their being regulated at the station to give a constant voltage at their feeding points. The distinction between the two classes of conductors will be rendered clearer from the following example.

Inelastic Conductors.   Economy of Copper.

Suppose it is required to supply current to a number of large consumers scattered irregularly over a district where it is permissible to run overhead wires, or underground cables independently of the street plan, then the arrangement requireing least copper would be that in which each consumer is connected direct to the central station by a separate wire, in which the maximum drop would be allowed.   In order to show that such a system requires a minimum weight of copper, it has only to be observed that any other mode of supplying any one of the loads from the central station, involves the addition of copper on two sides of a triangle, of which the direct feeder would form the third side.

Instead of an ordinary network the system would be reduced to a set of independent feeders radiating from the station, like the lines of a telephone exchange, and all the distributors would be eliminated.   This arrangement, involving the minimum of copper, might not be the cheapest, as the total length of cable laid (being the sum of all the feeders) might be considerably more than if they were employed with a network, and the expense of laying them might counterbalance the nominal saving in copper.

Such a system would be, under our definition, absolutely inelastic.   None of the feeders could assist each other in the event of fluctuations occurring at different points, and the only regulation possible would be by adjusting the pressures on individual feeders at the station.   An alternative method of dealing with the same consumers in the positions given would be to connect them all to one distributing main large enough to

prevent the drop of pressure at the *most distant* exceeding the prescribed amount, when all the full loads were on. In this case the elasticity would be perfect, but the amount of copper required would be very heavy. In general practice where a network is supplied by feeders the properties of both classes of conductor are utilised.

Limiting Length of Simple Distributor.

From the formula already established for a uniformly loaded two-wire distributor radiating direct from the central station or other point of supply, the cross-section was $S = \dfrac{C_0 L^2}{K v}$, and from this it will be seen that the volume of copper $\left(\dfrac{C_0 L^3}{K v} \right)$ increases as the cube of the distance Thus the limit of its range is soon reached, if regard is given to the capital cost, and feeders must then be used.

Employment of Elastic and Inelastic Feeders.

The effect of employing one or more feeders (elastic in the first instance) can be easily demonstrated.

If l is the original length supplied direct from the central station S (Fig. 7), and if it is then divided in two and the further
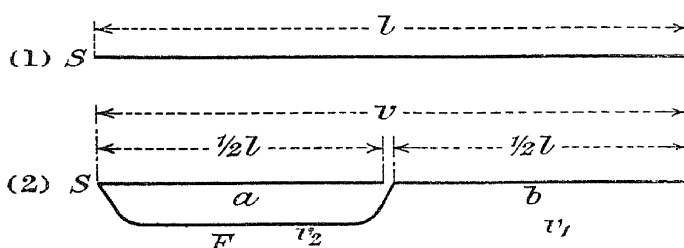
FIG 7.

portion is supplied by a feeder at one end, the relative volumes of copper in the two arrangements illustrate some important principles. The load is supposed to be uniform at c amperes per unit length, and the same proviso as to the total drop at any point not exceeding v applies to both. One conductor only of the two-wire system is considered.

The volume of copper in (1) is $\frac{1}{2}\frac{cl^3}{Kv}$.

The volume in (2) will depend on how the permitted voltage drop v is subdivided between the distributor b and feeder F.

It has a minimum value which is found as follows : The volume of copper in the main a, when we replace l in the general formula $\frac{1}{2}\frac{cl^3}{Kv}$ by $\frac{1}{2}l$, is $\frac{1}{16}\frac{cl^3}{Kv}$

Volume in the main b is similarly $\frac{1}{16}\frac{cl^3}{Kv_1}$, where v_1 is the drop to the far end.

The cross-section of the feeder F is $\frac{CL}{Kv_2}$, and its volume is $\frac{CL^2}{Kv_2}$. The current C, which it carries, is $\frac{1}{2}cl$, and L is $\frac{1}{2}l$.

The volume of F is therefore $\frac{1}{8}\frac{cl^3}{Kv_2}$, or $\frac{1}{8}\frac{cl^3}{K(v-v_1)}$, since v_2 is $v-v_1$.

The aggregate volume of a, b and F is—

$$\frac{1}{16}\frac{cl^3}{Kv}+\frac{1}{16}\frac{cl^3}{Kv_1}+\frac{1}{8}\frac{cl^3}{K(v-v_1)}.$$

We now require to determine the value of v_1, which will make the sum of the last two terms a minimum, and this will give the smallest aggregate volume, as the first part $\frac{1}{16}\frac{cl^3}{Kv}$ is constant. Simplifying, we obtain—

$$\frac{cl^3}{8K}\left(\frac{1}{2v_1}+\frac{1}{(v-v_1)}\right),$$

and differentiating the part in brackets with respect to v_1 and equating to zero we find—

$$(v-v_1)^2=2v_1{}^2, \text{ or } v_1=\frac{v}{2\cdot414},$$

$$v_2=v-v_1=v-\frac{v}{2\cdot414}=\frac{1\cdot414v}{2\cdot414}.$$

The respective volumes are now :—

For $a=\frac{1}{16}\frac{cl^3}{Kv}=0\cdot0625 \cdot \frac{cl^3}{Kv}$,

for $b=\frac{1}{16}\frac{cl^3}{Kv_1}=\frac{1}{16}\frac{cl^3\times2\cdot414}{Kv}=0\cdot1508\frac{cl^3}{Kv}$,

for F$=\frac{1}{8}\frac{cl^3}{K(v-v_1)}=\frac{1}{8}\frac{cl^3\times2\cdot414}{Kv\times1\cdot414}=0\cdot2134\frac{cl^3}{Kv}$.

Their sum is $0.4267 \dfrac{cl^3}{Kv}$, while the volume of the singly fed distributor was $0.5 \dfrac{cl^3}{Kv}$, and the relative saving is thus 14·6 per cent.

It is evident that both feeder and distributor here come under the definition of elastic mains, and the result given above indicates that no great saving in volume of copper can be effected by using an elastic conductor as a feeder. In this particular instance there might be a positive disadvantage in employing a feeder owing to the additional cost of laying it.

If, however, we make the feeder inelastic by allowing a considerable voltage drop in it, and provide for this by giving it a high E.M.F. at the station 'bus bars and by suitable regulation maintain the standard pressure at the feeding point a great diminution in volume of copper is the result. If v_2 in the feeder is made equal to $8v$ and the full drop v is allowed from the feeding point to the end of its distributor, the total copper becomes—

$$\text{Volume } a = \tfrac{1}{16}\, \frac{cl^3}{Kv} = 0.0625 \frac{cl^3}{Kv},$$

$$\text{Volume } b = \tfrac{1}{16} \cdot \frac{cl^3}{Kv} = 0.0625 \frac{cl^3}{Kv},$$

$$\text{Volume F} = \tfrac{1}{64} \cdot \frac{cl^3}{Kv} = 0.0156 \frac{cl^3}{Kv},$$

or altogether $$= 0.1406 \frac{cl^3}{Kv},$$

as compared with $0.4267 \dfrac{cl^3}{Kv}$ above.

These approximate figures are sufficient to show that by the association of both classes of conductor an enormous saving in the amount of copper can be effected. The only relative disadvantages of this arrangement are the cost of the power required to furnish the E.M.F. lost in the feeder, and the trouble and expense of regulating the voltage. An important application of this principle is seen in the return feeders for tram-

ways which are usually uneconomical for their purpose unless provided with an auxiliary E.M.F. from a booster.* This point is dealt with further in Chapter V.

Composition and Resolution of Load Currents in Distributors.

In considering the question of the best positions for feeding points generally we will first investigate the formulæ for the composition and resolution of currents taken off distributors.

Let AB be a distributor supplied at both ends either direct from two feeders or as an interconnector of the network (Fig. 8). Its cross-section is uniform, the total resistance being R and the load currents and resistances measured from A are c_1.. c_n and $r_1...r_n$ respectively. The P.D. between A and B which are supposed to be at different pressures is V_1-V_2. With an
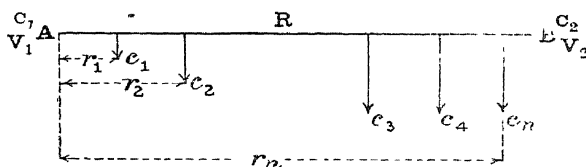
Fig. 8.

irregularly distributed load like that indicated one of the essentials is to know the position of the cutting point where the current changes its direction and begins to be supplied from B as well as A. This is obviously the point of maximum drop in the conductor.

For the purpose of the investigation any point such as c_2 can be assumed in the first instance and the current flowing in the distributor between c_1 and c_2 called x.

Then C_1, that part of the total current supplied from A

$$= c_1 + x \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and at the point B
$$C_2 = c_n + c_{n-1} + \ldots c_2 - x \quad . \quad . \quad (2)$$

---

* *See* Paper by Mr. H. F. Parshall, *Proc.* Inst.E.E., June, 1898 ; also Paper by Messrs. Cunliffe, *ibid.*, Dec., 1912.

As the drop from either end has to be the same at the cutting point—

$$V_1 - c_1 r_1 - x r_2 = V_2 - c_n (R - r_n) - c_{n-1}(R - r_{n-1}) \ldots$$
$$(c_2 - x)(R - r_2)$$

and $V_1 = V_2 - R \{c_n + c_{n-1} \ldots (c_2 - x)\} + c_n r_n + c_{-1} r_{n-1}$
$$\ldots + c_2 r_2 + c_1 r_1.$$

Substituting from (2)

$$V_1 = V_2 - RC_2 + \Sigma_1^n (cr),$$

$$\therefore \quad C_2 = \frac{V_2 - V_1}{R} + \frac{\Sigma_1^n (cr)}{R},$$

and $$C_1 = \Sigma_1^n c - \frac{V_2 - V_1}{R} - \frac{\Sigma_1^n (cr)}{R}.$$

Instead of dealing with the individual currents $c_1 \ldots c_n$ their resultant can be found from a similar formula to that for finding a mass centre. If R_1 is its distance from A

$$R_1 = \frac{\Sigma_1^n (cr)}{\Sigma c}, \text{ taking moments about A,}$$

and $$R_2 = \frac{\Sigma_1^n (cr)}{\Sigma c}, \text{ taking moments about B, gives its}$$

distance from B

In the above equations, instead of $\Sigma_1^n cr$ the equivalent $R_1 \Sigma_1^n c$ can be used without altering the values of C_2 and C_1. This proves that the resultant can be taken instead of the individual currents without any influence on the network beyond A and B. When these points are at different voltages the expression for C_2 and C_1 can be written in the forms :—

$$C_2 = \frac{V_2 - V_1}{R} + C \cdot \frac{R_1}{R},$$

$$C_1 = \frac{V_1 - V_2}{R} + C \cdot \frac{R_2}{R}, \text{ where } C = \Sigma_1^n c.$$

When the voltage is the same at each end $V_2 = V_1$, and the values of C_2 and C_1 are inversely proportionate to their distances from the resultant point. When

$$\frac{V_1 - V_2}{R} = C \cdot \frac{R_1}{R}$$

there is no component current from B, and $C_2 = 0$.

This simply means that the whole of the current taken by the consumers is supplied from A and the P.D. between the two points A and B is that caused by the load currents acting from A only. The rule may be stated generally as follows : The current entering one end of a distributor fed at both ends at different pressures may be considered as made up of two parts. The one part is the component of the load currents and the other is the current which would flow in the distributor if its ends were maintained at the actual P.D. without any of the load currents. This rule embodies the principle of what has been called the *superposition of currents* and it is of great use in the analysis of networks, as will be seen later. The true cutting point or point of minimum voltage is found by subtracting the various load currents c_1, c_2, &c., from C_1 until the difference becomes negative. The point where this occurs is always at one of the loads and the proportions of it supplied from A and B respectively are given by the above method.

EXAMPLE OF COMPOSITION AND RESOLUTION OF LOAD CURRENTS.

Fig. 9 represents a two-wire distributor AB 400 yards long, of uniform cross-section, with loads (stated in amperes) tapped off at the intervals shown.
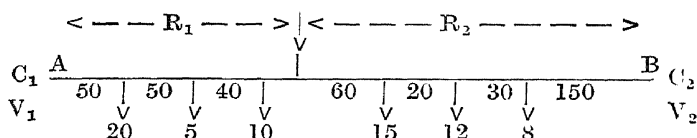
FIG. 9.

The first step is to find the position of the resultant of the load currents.

Reckoning from A its distance $R_1 = \dfrac{\Sigma c \cdot r}{\Sigma c}$.

As the main is uniform we can take the lengths l instead of the resistances r.

Thus
$$R_1 = \frac{\Sigma cl}{\Sigma c}$$

$\Sigma c \cdot l . = 20 \times 50 + 5 \times 100 + 10 \times 140 + 15 \times 200 + 12 \times 220 + 8 \times 250$

$= 10,540$, also $\Sigma c = C = 20 + 5 + 10 + 15 + 12 + 8 = 70$ amps.

Thus
$$R_1 = \frac{10,540}{70} = 150 \cdot 6 \text{ yards.}$$

Similarly by reckoning from B we find $R_2=249\cdot4$.   (The two together make 400 yds., which checks the arithmetical working, but it is sufficient to reckon from one end only in practice.)

$C_1=C \cdot \dfrac{R_2}{R}$ where R is the total resistance, or on our assumption the total length.   Hence

$$C_1=70 \cdot \frac{249\cdot4}{400}=43\cdot7 \text{ amperes,}$$

and $\qquad\qquad C_2=70-43\cdot7=26\ 3 \text{ amperes.}$

The cutting point between A and B when $V_1=V_2$ is found by starting from A and deducting the load currents from C_1 until the result becomes negative.

Thus $43\ 7-20-5-10-15$ is negative, and as the sign changes at load 15 this is the cutting point.

Here 8·7 amperes come from A and 6 3 amperes from B.   This can be checked thus : from A $20+5+10+8\ 7=43\cdot7$, and from B

$$8+12+6\ 3=26\ 3.$$

If the main is 0 1 section the drop is found as before from

$$v=2\frac{\Sigma c \cdot l}{Ks}=\frac{2\times 4{,}6\ '0}{40{,}000\times 0\ 1}=2\cdot3 \text{ volts,}$$

reckoning the distances from A.

Starting from B we find $v=\dfrac{2\times 4{,}640}{40{,}000\times 0\ 1}=2\ 3 \text{ volts.}$

The second operation is obviously unnecessary, but it is a useful check to show that the cutting point is calculated correctly.

Suppose now that A and B are at different potentials ; $V_2=97$ and $V_1=100$ volts.

The resultant currents are (1) $C_2=\dfrac{V_2-V_1}{R}+C\dfrac{R_1}{R}$.

We already know $C\dfrac{R_1}{R}$ to be 26·3 and the other portion

$$\frac{V_2-V_1}{R}=\frac{97-100}{R}=\frac{-3\times Ks}{2L} \left(\text{since } R=\frac{2L}{Ks}\right)$$

$$=\frac{-3\times 40{,}000\times 0\cdot1}{2\times 400}=-15.$$

Thus $\qquad\qquad C_2=-15+26\ 3=11\cdot3 \text{ amperes.}$

(2) $C_1=\dfrac{V_1-V_2}{R}+C \cdot \dfrac{R_2}{R}=+15+43\ 7=58\cdot7 \text{ amperes.}$

The cutting point is at load 12, since $11\ 3-8-12$ is negative, and 3·3 amperes come from B and 8·7 amperes from A.   The voltage drop from A to the cutting point works out at 3·9 and from B at 0·9 volt, the difference between them being, of course, 3 volts.

Position of Feeding Point with one Feeder only.

To avoid any confusion between the point where the resultant current acts and the cutting point, we notice, first of all, that the position of the resultant is constant for a definite arrangement of the loads. The position of the cutting point on a uniform main AB will vary in accordance with the positions of the loads relatively to the supply points A and B (Fig. 9).

Its position is also dependent on the relative voltages of A and B, as we have seen in the numerical example. In fact, if we regard the main as analogous to a loaded balance beam the resultant would be at the point of support, when the beam was in equilibrium.

The cutting point would not be coincident with the resultant unless A and B were at the same voltage, and the loads were
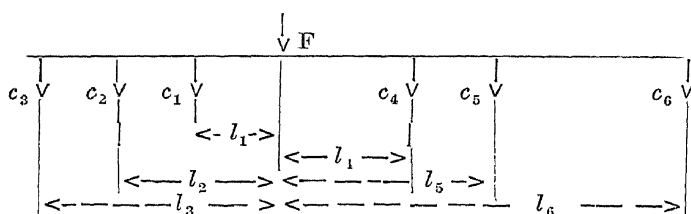
Fig. 10.

symmetrical in magnitude and position in going from A to B or *vice versa*. The best position for the single feeding point of an irregularly loaded main is coincident with that of the resultant current.

The definition of " best position " is that which entails the minimum volume of copper in the main. This statement can be proved as follows.

In Fig. 10 the two-wire main is fed at F and supplies load currents c_1—c_6 at distances l_1—l_6 respectively measured from F.

The drop from F to $c_3 = v = \dfrac{2}{Ks}(c_1 l_1 + c_2 l_2 + c_3 l_3)$, and to keep the cross-section, s, at a minimum v would have its highest permissible value.

Put $l_1=p.l_3$ and $l_2=q.l_3$ where p and q are constants,

then
$$s=\frac{2}{\mathrm{K}v}\ (c_1pl_3+c_2ql_3+c_3l_3)$$

and the volume of copper from F to c_3 is

$$s\times2l_3=\frac{4}{\mathrm{K}v}\ .\ (c_1p+c_2q+c_3)l_3{}^2=l_3{}^2\mathrm{M},$$

where M represents $\dfrac{4}{\mathrm{K}v}\ (c_1p+c_2q+c_3)$.

Similarly, if $l_4=f.l_6$ and $l_5=g.l_6$, the drop from F to c_6 being also v, the volume of the main on this side is

$$\frac{4}{\mathrm{K}v}\ .\ (c_4f+c_5g+c_6)l_6{}^2\ \text{or shortly}=l_6{}^2\mathrm{N}.$$

The aggregate volume is thus $\mathrm{M}l_3{}^2+\mathrm{N}l_6{}^2$.

On the analogy of the mechanical problem it is well-known that the value of $\mathrm{M}l_3{}^2+\mathrm{N}l_6{}^2$ is a minimum when l_3 and l_6 are measured from the mass-centre. In the present problem if we suppose F to be displaced from its position at the mass-centre a short distance h, we note that l_3 becomes l_3+h and l_6 becomes l_6-h.

The aggregate volumes would then be

$$\mathrm{M}(l_3+h)^2+\mathrm{N}(l_6-h)^2=\mathrm{M}l_3{}^2+2\mathrm{M}l_3h+\mathrm{M}h^2+\mathrm{N}l_6{}^2-2\mathrm{N}l_6h+\mathrm{N}h^2.$$

Now it is characteristic of the resultant point (or mass-centre) from which l_3 and l_6 are measured that $\mathrm{M}l_3=\mathrm{N}l_6$ since the drop v is the same either way to c_3 or c_6, and s is uniform. Hence the volume would be $\mathrm{M}l_3{}^2+\mathrm{N}l_6{}^2+(\mathrm{M}+\mathrm{N})h^2$ for a displacement h of the feed point.

This is obviously always greater than $\mathrm{M}l_3{}^2+\mathrm{N}l_6{}^2$, and thus the resultant point as feed point gives the minimum volume of copper. A large displacement of the feeder from its best position entails a rapid increase in volume of copper as this is proportional to the square of the displacement. The same principles indicate that the best position for the central station is, as regards volume of copper in the feeders, at the mass-centre of all the loads supplied.

Determination of best number of Feeding Points.

If the distributor is of considerable length it is necessary to have several feeders supplying it, and when it is uniformly

loaded an approximate formula can be established that will
indicate what is the best number of feeders to employ so that
the total cost of these and the distributors may be a minimum.
It might be repeated that an increase in the number of feeders,
although entailing a greater cost for themselves alone, permits
of a reduction in the cross-sections of the distributors, and thus
there must be a particular number of feeders which will give
the best result.   Let CD be the distributor of length L loaded
with c amperes per yard run with feeders at A and B (Fig. 11).
Taking the usual formula for the cost of any cable as laid $as+b$,
where s is the cross-section, a is a constant and b is the cost
per yard of making and laying, the cost of the distributors CD
can be written as $L(as+b)$.

But $\quad s = \frac{1}{2}\dfrac{cl^2}{Kv}$ as already found, and $l = \dfrac{L}{2n}$, where v is the

permissible drop and n is the number of feeders.

$$\therefore \quad s = \tfrac{1}{8}\frac{cL^2}{n^2 Kv}$$

and $$\text{cost} = L\left(\frac{acL^2}{8n^2 Kv} + b\right).$$

If the distributor forms part of a circle with the supply station
for centre the lengths of the feeders will all be the same, and
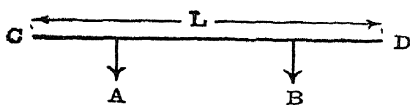
FIG. 11.

this would be approximately true also if the distributor is
straight but at a considerable distance from the station.

The cross-section of the feeder $s_f = \dfrac{C}{d}$, where C is the current

it carries and d is the most economical current density from
Kelvin's law.   If L_f is the constant length of a feeder the cost
of n feeders is $= nL_f(as_f + b)$.   But C, the current carried by
any feeder,

$$= \frac{cL}{n} \quad \text{and} \quad s_f = \frac{cL}{nd}.$$

Therefore total cost of feeders$=n\mathrm{L}_f\left(\dfrac{ac\mathrm{L}}{nd}+b\right).$

The aggregate cost of the system is, therefore,

$$n\mathrm{L}_f\left(\frac{ac\mathrm{L}}{nd}+b\right)+\mathrm{L}\left(\frac{ac\mathrm{L}^2}{8n^2\mathrm{K}v}+b\right)=f(n),$$

and it will have a minimum value when $\dfrac{df(n)}{dn}=0,$

or when

$$b\mathrm{L}_f-\tfrac{1}{4}\frac{ac\mathrm{L}^3}{\mathrm{K}vn^3}=0\ ;$$

and from this

$$n=\mathrm{L}\sqrt[3]{\frac{ac}{4\mathrm{K}vb\mathrm{L}}}.$$

As a numerical example take a portion of a circular main (L) 800 yds. long at a radius L_f 1,000 yds. from the station with a load of 1 ampere per yard run, and a maximum allowable drop of 2 volts. For certain classes of cable

$$a=\text{£}1,\ b=7/\text{-}=\text{£}0\cdot35.\quad \mathrm{K}=40{,}000$$

(all with yard and square inch units),

$$n=800\sqrt[3]{\frac{1\times1}{4\times40{,}000\times2\times0\cdot35\times1{,}000}}$$
$$=1\cdot7\ \text{approx.},$$

which means, as the nearest integer is 2, that two feeders give the most economical results.* The feeding points must be placed so as to divide the distributor into symmetrical parts. It will be noticed that when the number of feeding points is correctly ascertained the best lengths for the distributors are at once indicated.

Graphical Method for finding best position of one or more Feeding Points.

If the load is disposed too irregularly to permit of the symmetrical postions of the two feeders giving the smallest cross-sections of the distributors for a 2-volt drop the best feeding points must be found by trial and the simplest way of doing it is graphically.

In dealing with this question let us begin with the arrangement of one feeder supplying a ring main or a dis-

---

* Observe that, when the feeders and distributor are of different classes, a, in the formula for n, refers to the distributor and b to the feeder.

trict forming a circular belt with the station at its centre. The procedure algebraically would be to cut the ring at any point, develop it into a straight line, and find the position of the resultant current, with the further assumption that half the load at the cutting point was supplied from each side. As already indicated the position of the feeder thus found gives the minimum drop for any such particular case and is the most advantageous. In order to complete the investigation it is necessary to assume the cutting point at every load, for each of which another position for the feeder would be obtained. The position giving absolutely the lowest drop is the best
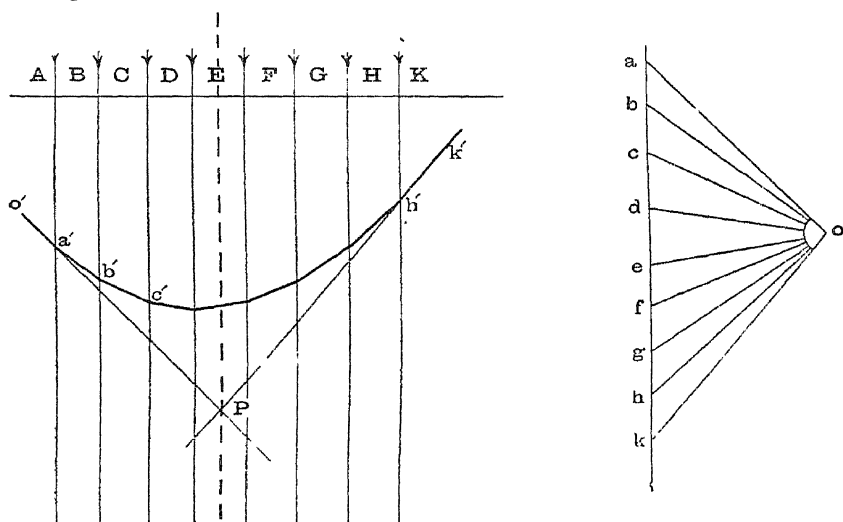
Fig. 12.

possible, but the only method of ascertaining this is by laboriously calculating the drop from the feeding point to the cutting point with every alternative and noting which is the smallest. In a general way it is easy to see that the most favourable arrangement is when the feeder is run to the point where the load is densest, so that the sum of the moments of the remaining loads about that point is a minimum.

To solve such problems graphically a polygon of currents and a funicular polygon of drops have to be constructed for each assumed cutting point, the method being analogous to that for finding the bending moment of a cantilever.

A clear and full description of graphical calculations with quantities of the nature of forces or currents will be found in Henrici and Turner's " Vectors and Rotors " (Arnold).

It will be sufficient here to give the steps of the construction in a form suitable for the present problem without the mathematical proof.

The simplest instance of the use of graphical methods is to find the resultant of a number of parallel forces, AB, BC, CD, &c., all acting in one plane.   (Fig. 12.)

Take a line parallel to the direction of the forces and set off on it the various lengths *ab, bc, cd, de,* &c., representing the
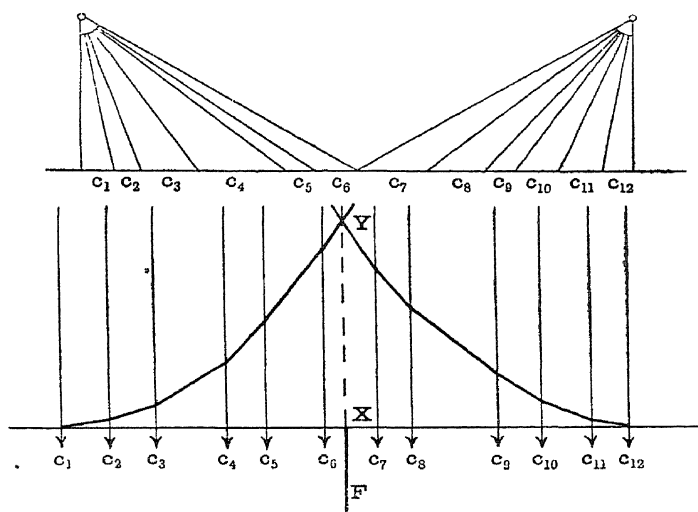
FIG. 13.

magnitudes of the forces to some convenient scale ; then choose a pole 0 in any position and draw lines from it to each point *a, b, c, d,* &c.

Through each of the extended lines AB, BC, CD, &c., draw parallels, or *lines at right angles* to *oa, ob, oc,* &c.   Thus *o'a'* is parallel to *oa, a'b'* to *ob, b'c'* to *oc,* and so on.

The first and last lines *o'a'* and *h'k'* when produced will meet each other in the point P, through which the resultant of all the forces will pass.

The broken line *o'a'b'c'—h'k'* is called the funicular or link polygon.

The same construction holds for the resultant of a number of load currents taken off a distributor.

The graphical principle is employed in Fig. 13 to find the position of a single feeder. The construction is a modification of Fig. 12, with a view to simplification, when two or more feeders are being considered later. The values of the currents are first set off to scale on the horizontal line in the upper half of the diagram. The two poles of the polygon of currents are chosen so that the polar distances from the horizontal line of currents are the same, and each of the starting lines (for c_1 and
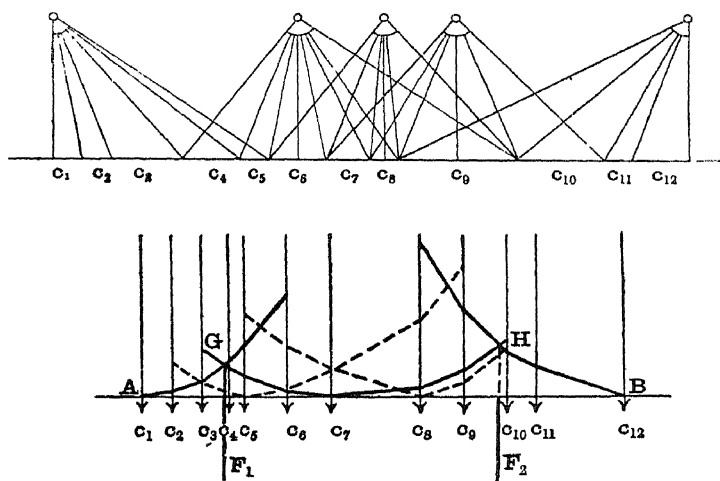
FIG. 14.

c_{12} respectively) are at right angles to the horizontal, and, therefore, parallel to each other. The funicular polygon is constructed by taking lines at *right angles* to the rays of the polygon of currents, the rest of the procedure being analogous to Fig. 12.

The position of the feeding point or resultant of all the currents is found by the intersection Y of the two funicular polygons, which were commenced at c_1 and c_{12}, and the intercept XY represents the drop to these points. If the value of this drop is v, the drop at any other point in the distributor is found by deducting from v the intercept between the funicular polygon and the horizontal line representing the conductor.

The graphic method is useful when the number of feeders n has been determined from the formula

$$n = L \sqrt[3]{\frac{ac}{4KvbL_f}}$$

(which implies that the actual distribution of the load can without great inaccuracy be replaced by an uniform equivalent) and it is only necessary then to consider the best positions for the feeders. The complete solution by this method involves the drawing of polygons of current and funicular polygons for each assumed cutting point, but if they are all drawn with the same polar distance and the starting lines parallel the particular case giving minimum drop can be recognised by inspection, as the drops are then directly comparable. For a distributing main, AB (Fig. 14), of uniform (but undetermined) cross-section, loaded as shown, supplied by two feeders, the construction would be as follows :—

Draw funicular polygons passing through A and B and then draw tentatively several similar polygons for the points near the middle so that any pair of the intercepts between the points of intersection G and H of the funicular polygons and the line AB are equal, or approximately so. The feeders should run to the corresponding points on the line AB to give a minimum cross-section to the distributor. If r is the resistance per yard, by taking the drop v from F_1 or F_2 its value, and hence that of the cross-section can be calculated from the formula $\Sigma(r \times cl) = v$, where v is the maximum allowable drop and l is the distance of each load from F.

Position of Feeding Points for Ring Main.

If AB instead of being a short length of main is circular with the supply station at the centre the procedure is a little more complicated.

It must first be cut and developed into a straight line, and if there are x load points, for each of these a polygon of currents and a funicular polygon must be drawn to the right and left of each point.

The x pairs of funicular polygons will intersect in x points. When there is to be only one feeder, as already proved, the position of the intersection where the intercept is least will give the best feeding point. When there are two feeders it will be

noticed that there are $x/2$ pairs of points of intersection corresponding to the $x/2$ possible solutions of the problem.   By an examination of the several pairs of intercepts it can be seen which gives the minimum drops, and thus the correct positions for the two feeders are indicated.   The graphical construction is given in Fig. 15.

An extension of the same reasoning can be used for any number of feeders.   (*L'Industrie Électrique*, August, 1903.)
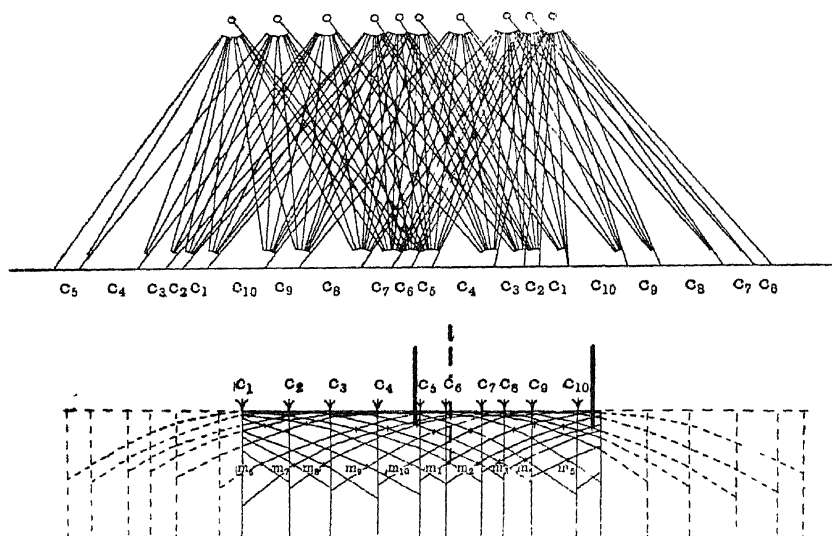
Fig. 15.

Application of Graphical Process to Tramway Feeders.

One example of the application of these principles practically is to find the best position of a tramway return feeder.   It is due to Mr. A. P. Trotter, and will be found described in the *Proceedings* Inst.Elec.Eng., June, 1898.   The most noticeable feature of Mr. Trotter's method is the employment of a template of card following the curve of differences of potential, equivalent to the funicular polygon above.   This can be used for drawing the curves of drop for any assumed position of the feeder and under the given conditions that the voltage at any point between the rail and earth shall not be more than, say, 5 volts.   It is only possible with a symmetrical

distribution of the cars on the track to substitute the use of a template for the purely graphical construction already given.

To explain more fully the function of this curved template we refer to the formula for the drop in a uniformly loaded conductor, which is $v = \frac{1}{2} \dfrac{C_0 L^2}{Ks}$.

With the tramway track as return conductor the cross-section s is constant, and if the return currents of the cars can be approximately replaced by an equivalent uniform value per yard run, C_0 can also be considered constant.

Thus, $v = \frac{1}{2} \dfrac{C_0 L^2}{Ks}$ may be written $v = QL^2$, where Q is a constant.
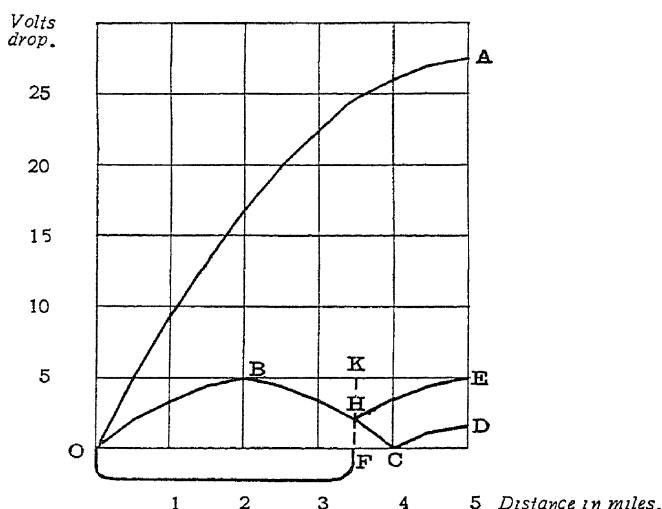
FIG. 16.

This is the equation of a parabola with its vertex at the origin of the axes of v and L, the former being vertical and the latter horizontal. From whichever point we start with v, such as A, B, E or D (Fig. 16), the same parabolic outline, if superimposed on any length L under consideration, will give graphically the voltage drop at every point along the length.

In the case worked out by Mr. Trotter, where the total drop without a feeder would have been $27\frac{1}{2}$ volts in a track 5 miles long, it can be proved by his quasi-graphical process that the feeder is best situated when connected up to the track at a.

point, F, $3\frac{1}{2}$ miles from the central station. As will be seen from an inspection of the diagram (Fig. 16) this satisfies the condition that the intercept HK between the point of intersection of the curves of drop and the datum line (5 volts in this case) is a minimum. As Mr. Trotter points out, this problem is restricted to the selection of one feeding point, which will give a minimum volume of copper in the *feeder*. As the cross-section of the distributor—*i.e.*, the rails—is fixed by mechanical requirements in this case, it cannot be calculated for any economic current density.

Although these methods for the location of feeding points have been dealt with at some length it is not with a view to urge their use indiscriminately but rather to demonstrate the general aim of endeavouring to associate feeders and distributors in the most efficient way with definite data so that a minimum amount of copper is required.

Principles controlling the amount of Network Fed from each Feeder.

It will be noticed in what precedes that the distributors have mostly been taken as running at right angles to the feeders, or
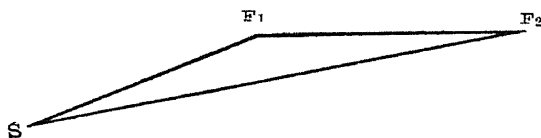
FIG. 17.

nearly so. But in practice there are many of them running in various directions relatively to the feeders, and it is interesting to trace the law of economy applicable to this arrangement. The whole area of distribution has also been assumed to be split up into concentric zones, but the present case is somewhat more general. The problem is to determine the best feeding areas round each feeder, or the boundary line for any one feeder. This line passes through the cutting points between the feeder under consideration and the neighbouring ones. To begin with, it is at once clear, if S (Fig. 17) is the central station and $F_1 F_2$ is the distributor fed at F_1 and F_2 at the same pressure, that it will not be economical to carry a large pro-

portion of the current by feeder direct to F_2, and then transmit it backwards along the distributor. On the other hand, if the bulk is fed in at F_1 the distributor will have to be heavier owing to the cutting point being shifted towards F_2. The relative values of the two feeder currents and the position of the cutting point depend on several factors.

The volume of copper in any conductor of length L and cross-section s in which there is a current C flowing and causing a drop of pressure v is, as before

$$=\frac{CL^2}{Kv}.$$

Thus for any current C the volume of copper required to convey it to any length L is proportional to $\frac{L^2}{v}$. In Fig. 18, F_1F_2 is a distributor supplied from the central station S by two feeders of different lengths D_1 and D_2, and V_f and V_d are the voltage drops in the feeders and distributor respectively. V_f in general is much higher than V_d, the ratio being of the order of 4 to 1, since V_f is regulated from the station 'bus bars, while V_d is limited to 3 per cent.

Taking an installation at any point in the distributor, $F_1 F_2$, its current C may reach it by two alternative paths.

If supplied through D_1 it will mean an increase in the volume of copper in that feeder equal to CD_1^2/KV_f. If supplied through D_2 the increase in volume of copper would be CD_2^2/KV_f. Thus the saving in copper by supplying through D_1, if the feeders alone are considered would be $\frac{C}{KV_f}(D_2^2-D_1^2)$. The volume of copper required in the distributor between F_1 and F_2 of length L would be CL^2/KV_d, and a certain point X can be found where

$$\frac{CL^2}{KV_d}=\frac{C}{KV_f}(D_2^2-D_1^2).$$

At such a point there would be no advantage between the two alternative paths, for it necessitates as much copper to supply one additional ampere of load up to X through the length D_1 as up to F_2 through the length D_2. The distance L can be calculated from the simplified expression :—

$$L^2=\frac{V_d}{V_f}(D_2^2-D_1^2).$$

The remaining portion of the distributor XF_2 would be supplied most economically if half its load were taken from X and the remainder from F_2.   Thus the true cutting point delimiting the distances fed from F_1 and F_2 respectively would be at M, midway between X and F_2.   A similar treatment of any other branches of the network between F_1 and F_2 or any other feeders contiguous to F_1 would lead to a series of cutting points, which when joined together by a line will form a natural frontier to the feeding area of F_1.

As an example, let $D_1 = 400$ yds., $D_2 = 500$ yds., V_d at 3 per cent. of the supply pressure of 400 volts $= 12$ volts, V_f at 10 per cent. of 400 volts $= 40$ volts.

Then

$$L^2 = \frac{V_d}{V_f}(D_2{}^2 - D_1{}^2)$$

becomes

$$= \frac{12}{40}(500^2 - 400^2),$$

from which $L = 164$ yds.

The total distance between F_1 and F_2 in this case is 300 yds. (as the feeder D_1 happens to be at right angles to the distributor), and therefore to find the cutting point M we take half of $300 - 164 = \dfrac{136}{2} = 68$, which means that it is 68 yds. from F_2 ; and current via D_1 is sent economically to a distance of 232 yds. from the feeding point F_1.
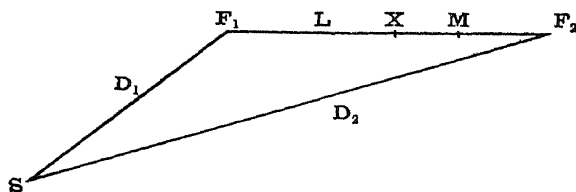
FIG. 18

In order to ensure a minimum volume of copper, therefore, it is essential that no customer properly belonging to one feeder area should obtain current from any other.

The surest way of effecting this is not to permit any distributor to cross from one area into the next.   This leads to an arrangement of independent feeders with a special voltage regulation for each, and whatever objections may be urged against it on the score of insecurity of running or want of elasticity, the fact remains that such a subdivision of the distribution areas tends to a minimum volume of copper in the

feeders and distributors collectively. (A more extended investigation of this problem by Dr. E. Mullendorff will be found in the *Elektrotechnische Zeitschrift*, 1904, Nos. 15 and 46.)

Apart from the algebraical aspect of the question it is well known in practice that the feeders near the station ought to be allowed to feed outwards to a much greater length than the more remote ones feed backwards.

In modern distribution systems the feeder frontier lines have to be determined in any case, in order to comply with the Board of Trade regulations requiring the insertion of fuses at the cutting points between all feeders so as to limit the district affected in the event of the failure of any one feeder.

It seems a wise policy in laying out a new district to fix before hand where the feeder areas ought to abut, and the condition of minimum copper is probably the most reasonable one for defining these areas.

The arguments based on security of running and satisfactory voltage regulation are discussed later, together with the practical considerations which influence the choice of feeding points.

CHAPTER IV.

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THE DESIGN OF FEEDERS.

Law of Economy.

When a network has been split up sufficiently to be able to assign approximate values to the currents in the various feeders, the next question to be considered is the determination of the cross-sections of the latter. As already seen, the technical conditions of voltage drop and temperature rise are all that are necessary for fixing the dimensions of distributors. In certain circumstances, by suitably proportioning the cross-sections which satisfy the technical conditions, an economy of material can be effected, but for the feeders of a network, or for long-distance transmission mains, a new element enters the problem. This is the commercial efficiency of the cable, the value of which depends on two factors. The first of these is the cost of the energy lost in transmitting the current to the feeding point, which is proportional to $C^2 r$. Owing to a feeder being purposely made an inelastic conductor, the total amount of drop (Cr) in it does not affect directly the voltage in the network, and, except for reasons of economy now to be considered, the drop is subject to but little restriction.

The second factor is the annual charge for interest, sinking fund and depreciation on the cable, which is represented by a percentage on its capital cost. If more copper is put into the cable it will absorb less energy, but the capital cost and its annual charges will be increased. Consequently, there must exist a relation between them which will give the best cross-section of cable to employ, so that the total annual expenses for energy lost and investment provided are a minimum. The solution of the problem was first given by Lord Kelvin, and is called Kelvin's Law.

In order to discuss its application for central-station conditions the proof of the law in the following form is found convenient.

In the first place, the cost of the energy lost must be re-
garded as made up of two parts, following the principles of
the maximum-demand system, which are now too well known
to require a detailed explanation.

The " standing charge " part of the energy cost is

$$C^2 rIp \left(\text{or since } r = \frac{l}{Ks} \right) = \frac{C^2 lIp}{Ks}.$$

In this expression l is the length of the feeder, s is the
cross-section, I is the capital cost per watt of the additional
plant, buildings, and other stand-by items necessitated by the
" demand " of the cable losses. No part of the stand-by
charges due to the capital cost of the cable network itself is
included in this item, but the demand on the station plant has
to be taken at its full value without any allowance for diversity
factor, as, owing to their very nature, the cable losses are
highest at the time of peak load. An annual percentage, p, has
to be reckoned on the investment so as to cover these charges.

The " running charge " part is given by

$$C^2 rNt, \text{ or } \frac{C^2 Ntl}{Ks},$$

where N is the number of hours that would have to be run at
the maximum load C, in order to have the same energy loss in
transmission as with the varying load, and t is the net running
cost per watt-hour obtained from the analysis of the total works
cost by the usual methods. The equivalent number of hours N
can be calculated by the method given later, but to simplify
the solution of the problem in the first instance C may be taken
as constant.

The total annual cost of energy lost in a cable of length l is
therefore,

$$\frac{C^2 lIp}{Ks} + \frac{C^2 Ntl}{Ks}.$$

The debit to be made against the cable on account of its own
capital cost is given by $l(as+b)p$, where s is the cross-section,
a and b are constants, and p is the annual percentage to cover
interest and depreciation , and it may be taken with sufficient
accuracy to be the same as the percentage on the plant in-
vestment in the formula immediately preceding.

It is well known that the cost per yard of any cable can be
expressed as $as+b$, provided all the sizes of s are confined to

the same *class* of manufacture, and that those under considera-
tion do not vary too widely amongst themselves.   Although
the formula might be true of sizes from 0·2 to 0·5, say, and
again from 0·75 to 1, it would not cover the whole range from
0·1 to 1.   The " constant " b usually represents the practically
invariable cost of making up the copper, insulation and lead
into a cable, but for our present purpose it has a more extensive
meaning, and covers besides the costs of laying and reinstating
and providing conduits, if any.   Thus the aggregate annual
charges against the cable are $(as+b)pl+\dfrac{C^2Ipl}{Ks}+\dfrac{C^2Ntl}{Ks}$.   .   (1)

To obviate any confusion in units, a and b must be in pence
per yard, l in yards, s in square inches, N in hours, t in pence
per watt-hour, I in pence per watt, and K a constant ($=40,000$)
based on yards and square inches for l and s respectively.

The two ways in which the problem presents itself are (a)
when the current C is constant and s has to be determined, or
(b) when a cable of section s is already laid and the most
economical current to transmit by it is required.   For either
alternative, if V is the 'bus-bar pressure, the value of the energy
transmitted is CNtV (at cost price), and the commercial
efficiency is stated thus :

$$\frac{\text{value of actual output}}{\text{value of input}}=\frac{CNtV-\left\{(as+b)pl+\dfrac{C^2Ipl}{Ks}+\dfrac{C^2Ntl}{Ks}\right\}}{CNtV}$$

$$=1-\frac{1}{VNt}\left\{(as+b)\frac{pl}{C}+\frac{C^2Ipl}{KsC}+\frac{C^2Ntl}{KsC}\right\}.\quad .\quad .\quad (2)$$

In case (a), where C is given and the best value of s has to be
found, this can be done by differentiating the expression in
brackets with respect to s and equating to 0, for when this has
a minimum value the ratio of output to input or the efficiency
will obviously be a maximum.

The result of differentiating is that

$$s^2=C^2\frac{Ip+Nt}{apK},\text{ or }s=C\sqrt{\frac{Ip+Nt}{apK}}$$

and $\dfrac{C}{s}$ or current density $=\sqrt{\dfrac{apK}{Ip+Nt}}.$.   .   .   .   .   .   (3)

The expression shows that the economical current density is independent of the length of the cable, and its form indicates clearly the opposing influences of the two components of the total cost, so that $\sqrt{apK}$ may be called the " investment loss factor " and $\sqrt{Ip+Nt}$ the " energy loss factor."

In case (*b*) where a cable of section *s* is already laid and the best current C has to be found, the aggregate loss must be treated as a function of the variable C, and when $\dfrac{df(\mathrm{C})}{d\mathrm{C}}$ is a minimum the efficiency will be a maximum.

After differentiating $f(\mathrm{C})$ and equating to 0, we find

$$C^2 = \frac{(as+b)spK}{Ip+Nt}$$

and $\dfrac{C}{s} =$ current density $= \mathrm{D} = \sqrt{\dfrac{apK}{Ip+Nt} + \dfrac{bpK}{s(Ip+Nt)}}$, which

gives, for a feeder carrying a maximum load, C, the cross-section $s = \dfrac{C}{D}$. . . . . (4)

Statement of Kelvin's Law.

Some interesting results are obtainable by a study of these formulæ. By substituting C in terms of *s* from (3) in the expression for the total losses (1), it becomes apparent that the best value of *s* is when the cost of the energy loss in the cable is equal to *apsl*, or that portion of the annual charges against the cable, which is proportional to the cross-section of the conductor. This is the ordinary statement of Kelvin's law.

Using the relation between C and *s* in (4), when substituting in (1), it is seen that the cost of the energy loss is equal to the total annual charges against the cable as manufactured and laid, and not merely to that part of them which is directly proportional to the cross-section of the conductor.

The two formulæ yield different values for the current density, depending on whether the current or the cross-section is the independent variable. This apparent discrepancy is due to the fact that to the cost of *any* cross-section obtained from (3) there must always be added the fixed charge per yard represented by *b* before the conductor can have any practical utility. Putting it in another way, if C is given and *s* is determined from (3), and its value used in (4), the value of the

current C′ obtained differs from C by an amount depending on the value of b and s. But if the necessary substitutions are made in the expression for *efficiency* (2), the two values of the latter obtained do not differ much.

The problem for the mains engineer usually takes the form of ascertaining what is the current that can be most economically sent through an existing feeder in order to determine whether it is necessary to increase its cross-section or to lay additional feeders to suitable points elsewhere. This depends on the current density found from (4), and its value is higher than that derived from the ordinary statement of Kelvin's law.

The contrast between the two solutions, somewhat puzzling at first sight, can be rendered clearer if the attention is fixed on the independent variable. As soon as the network and its feeders have a real existence, the problem, with an actively developing business, must be that of ascertaining what is the greatest current that can economically be delivered by the feeders without adding to their number or drawing in more copper. To satisfy this condition the current density found from (4) should be employed. The reason for this is that, with public supply undertakings, the loads on the feeders cannot be fixed at an ultimate constant figure (*i.e.*, C is indefinite), but they are all subject to increase with the growth of the demands in their several districts. When (b), or the cost of laying, provision of ducts, &c., is great, the current density is correspondingly high.

Law of Economy with Variable Load.

Under certain circumstances, as, for instance, with a water-power station and electric transmission, C has a definite value, and Kelvin's law, as stated in (3) is directly applicable. There the b term does not influence the choice of the current density. Furthermore, C is not only definite, but in such a case it is usually constant, a battery being used to store the surplus energy at times of light load. Thus no correction of the formula for variability of load has to be considered. On the other hand, with the variable load conditions that prevail in ordinary station supply, it is necessary to find the number of hours N during which the feeders would have to run at the maximum load C, so that the energy loss might be equal to

that which actually occurs. The annual loss in a feeder is represented by $r\Sigma(c^2h)$, where r is its resistance and c the variable value of the current, which may be supposed constant over a short interval of time, h—say one hour.

It is an arduous task to evaluate c^2 for each of the 8,760 hours in the year, but the following simplification gives accurate enough results.

The expression $\Sigma(c^2h)$ may be written $C^2\Sigma\left\{\left(\dfrac{c}{C}\right)^2 h\right\}$. The ratio of c, the actual current, to C, the maximum current, as well as the interval of time it covered, can be obtained from the " annual load curve " of the central station, which the feeder load curves may be assumed to follow closely. The
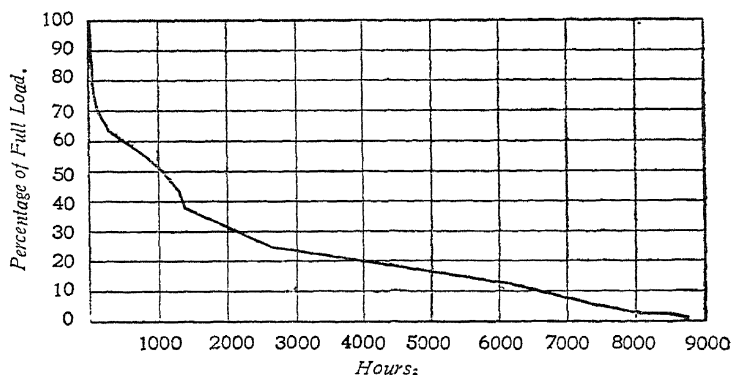
FIG. 19.

" annual load curve " is a graphical summation of all the daily load curves. It indicates the variation in the load throughout the whole year, and the total number of hours duration of every percentage of the maximum load. Further useful information regarding this curve is given in a Paper by A. Wright, *Journal* Inst. E.E., March, 1902.

The value of $\Sigma\left\{\left(\dfrac{c}{C}\right)^2 h\right\}$ derived from this curve, is equal to N—the number of hours of the maximum load C, which would entail the same annual loss as that due to the varying loads.

From the annual load curve given in the figure (Fig. 19), representing a load factor of 21 per cent., the value of N obtained is about 800 hours.

Current Density affected by several Factors.

In general, the values of the different terms of the expression for current density, $\sqrt{\dfrac{ap\mathrm{K}}{\mathrm{I}p+\mathrm{N}t}+\dfrac{bp\mathrm{K}}{s(\mathrm{I}p+\mathrm{N}t)}}$, depend on several circumstances, chief amongst which are the size of the station and the number of years it has been running. Dealing with them seriatim, in the numerator there is first to be considered the term a, which is proportional directly to the area of copper. Although copper is sometimes subject to remarkable fluctuations in price, a is a quantity that is fairly constant. Large cable schemes would be kept in abeyance while the price of copper was abnormally high, but, should this be impossible, the influence of the high value of a would be to increase the economical current density. As the cable investment in feeders is permanent, except with a draw-in system, this effect of increasing the current density could not afterwards be nullified.

The percentage p in both numerator and denominator may be taken as 8 per cent. to cover interest, sinking fund and depreciation.

The investment in station plant to provide for the peak load demand of the cable losses will depend a great deal on the size of the station. For a small town I will be about £30 per kilowatt, diminishing to £20 or less for a large station equipped with modern plant. A well designed large power station erected in 1915-16 cost considerably less than £10 per kilowatt.

The value of N, as already shown, depends in a somewhat complex fashion on the load factor, but it may be stated generally that when the load factor is high N will also be high, although not in a true linear ratio. Thus, for a load consisting chiefly of motors, N is large, and it would give greater economy to run at a lower current density than on a lighting load.

The value of t (the net running cost per watt-hour) is also affected by the load factor. Usually it will be of the order of 0·8d. per kilowatt-hour for an ordinary supply station, with a limiting value of 0·2d. to 0·1d. per kilowatt hour for the largest modern installations, with exceptionally good load factors. In deciding upon the best current density for feeders, while a network is still in the stage of design, it is necessary

to weigh all these circumstances, together with the probable developments of the load that will ultimately take place in the area.

The value which would satisfy the conditions in the early days might not necessarily prove correct for feeders added later ; but, fortunately, the variations in the different factors naturally tend to neutralise each other, and thus the current density originally chosen may fulfil the later requirements very closely. The rise in load factor, which normally occurs as the station grows, will increase N, but it will cause a diminution in running costs t, and the increase in size of the station will reduce the investment per kilowatt (I). Thus the aggregate value of the expression $Ip+Nt$ may remain fairly constant.

The influence of the cost of laying is apparent in the second part of the expression. As b is more or less of a constant, its value should be kept as low as possible, so that the net efficiency of the cable may be high. For cable of small cross-section it increases the economic current density to a very marked extent.

Kelvin's Law independent of Supply Voltage.

The formula, it will be noticed, does not include any term depending directly on the voltage of supply. Its effect is implied, however, as the value of the current for the supply of the same number of consuming devices varies inversely as the voltage. The selection of the best voltage for economy opens up a very wide question. For a low tension network certain values have long been standardised, the tendency being to get as near as possible to the legal limit of 250 volts.

In the feeders themselves the field of selection is much more extensive, as by the use of transforming devices, with or without sub-stations, any form of current or value of pressure can be adopted.

The final decision will rest on the results obtained by trying various alternatives : (*a*) Direct feeders ; (*b*) high-tension feeders with static transformers ; or (*c*) high-tension transmission with rotaries in sub-stations. There is no golden rule, either mathematical or otherwise, and nothing can obviate the necessity of trial calculations taking each system in turn and various voltages for each.

Kelvin's law will determine in any particular case which current density is the best at a definite voltage, and in the final comparison the system and voltage entailing the smallest aggregate annual expenditure ought to be the one selected, at least on the ground of economy.

It will be evident that the formulæ just investigated lead to values of the current density which are relatively, but not absolutely, the best. They have only a comparatively narrow application—*i.e.*, when the voltage is fixed—and if the object aimed at is to get the cheapest possible feeder system, the initial voltage and methods of transforming it down to that of the network must necessarily be considered.

Kelvin's Law in Practice.

It is seldom in the retail business of electricity supply that elaborate calculations of current density are entered upon, and it is customary in the case of the larger feeders to run them up to the limit of safety against temperature rise. For the smaller feeders, where higher densities are permissible, the easily-remembered figure of 1,000 amperes per square inch is usually worked to. Most frequently it happens that questions relating to feeders are thrust upon the mains engineer owing to complaints of voltage fluctuations in certain districts, and he is obliged to reinforce his feeder system with the voltage chart in view, rather than calculations of efficiency.

From the following examples it will be seen that the empirical rules above referred to conform more closely to the formulæ than might be expected. With a standard type of single cable, employed as a low-tension feeder,

$$a = 16s.\ 8d.\ \text{per yard and } b = 6s.\ 8d.\ \text{per yard.}$$

In the early stages of the business N=600 hours approximately, while t, the net running cost, is 0·8d. per kilowatt-hour. I is £50 per kilowatt and p is 8 per cent., from which Ip is 0·96d. per watt per annum. Then the current density, from the formula

$$\frac{C}{s} = \sqrt{\frac{ap\mathrm{K}}{\mathrm{I}p + \mathrm{N}t} + \frac{bp\mathrm{K}}{s(\mathrm{I}p + \mathrm{N}t)}}$$

for a feeder of 0·5 in. cross-section, becomes

$$\sqrt{\dfrac{200 \times \dfrac{8}{100} \times 40{,}000}{0{\cdot}96 + 0{\cdot}48} + \dfrac{80 \times \dfrac{8}{100} \times 40{,}000}{0{\cdot}5(0{\cdot}96 + 0{\cdot}48)}}$$

$$= \sqrt{\dfrac{640{,}000 + 512{,}000}{1{\cdot}44}}$$

$$= \dfrac{1{,}075}{1{\cdot}2} = 896 \text{ amps. per sq. in. (approx.)} \qquad . \quad . \quad (1)$$

If the cable were 0·25 instead of 0·5, the figures would be

$$\dfrac{C}{s} = \sqrt{\dfrac{640{,}000 + 1{,}024{,}000}{1{\cdot}44}} = \dfrac{1{,}300}{1{\cdot}2} = 1{,}080 \text{ amps. per sq. in. } (2)$$

When the business is more fully developed the quantities I, N and t may become I=£25 per kilowatt and Ip=0·48d. per watt per annum, N=800 hours, t=0·4d. Then, for a 0·5 cable the current density will be

$$1{,}095 \text{ amps. per sq. in.} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and for 0·25 1,460 amps. per sq. in. . . . . . . (4)

From information kindly supplied by Mr. J. R. Beard we are enabled to give some figures relating to the economic current density for the high-tension feeders of one of the large power schemes in the North of England.

This part of the transmission scheme is at 6,000 volts three-phase, and for a three-core cable round about 0·1 cross-section the cost was 600s.+125 pence per yard, including excavation and laying.

The value of Ip is 0·456d. per watt. N, on account of the very high load factor, is 2,190 hours, while the net running costs are as low as 0·1d. per Kelvin or 0·0001d. per watt-hour. The percentage p, applying to the cable investment, is taken as 7.

As the cost per yard is for a three-core cable complete, the term $(Ip+Nt)$ must be multiplied by 3, to cover the energy losses in all three cores.   The formula then becomes

$$\frac{C}{s}=\sqrt{\frac{ap\text{K}}{3(Ip+Nt)}+\frac{bp\text{K}}{s(Ip+Nt)3}}$$

$$=\sqrt{\frac{600\times0\cdot07\times40,000}{3(0\cdot456+2,190\times0\cdot0001)}+\frac{125\times0\cdot07\times40,000}{0\cdot1(0\cdot456+2,190\times0\cdot0001)3}},$$

from which $\dfrac{C}{s}$ is found to be 1,600 amps. per sq. inch   .   (5)

Even for this small cross-section the current density is quite high enough for safe working.

Cross-sections of Feeders dependent on Temperature Rise instead of Economical Current Density.

Examining these results in relation to the current densities allowable without exceeding the safe temperature rise (which are 1,000 amperes per square inch for 0·25 and 800 for 0·5, with vulcanised bitumen insulation), it is remarkable how closely the figures in cases 1 and 2 agree with the latter.

In cases 3 and 4, which refer to a station of moderate size in a later stage of development, the economic values tend to exceed those permissible.   Still more is this true in case 5, so that generally it is sufficient to take the values defined by temperature rise as a guide for the current density in feeders. There is always the strong probability that, with a natural healthy development of the undertaking, the densities that satisfy Kelvin's law will exceed these figures.   This applies *a fortiori* to large power distribution undertakings, where the capital per kilowatt and the cost per unit tend to minimum values.   Thus, in practice, the mains engineer is spared the ordeal of strictly applying Kelvin's law, as in many cases (more particularly with V.B. insulation or multi-conductor type) it is over ruled by the physical disability of the cable to withstand the rise of temperature which it would entail.

With overhead wires the question of temperature is a secondary one, and the economic considerations predominate.

Value of Current Density with a Number of Feeders of Unequal Length.

The foregoing investigation has been confined to a single trunk main or feeder. But if a number of feeders of different lengths supply a network from the same central station, so as to give the same voltage at the feeding points, one of two things must happen. (1) Either the current density which gives the greatest economy is employed for all of them, and the drop in each will be different, since

$$v = \frac{Cl}{sK} = \frac{l}{K} \times \text{current density},$$

and the cross-section of each feeder would be given by

$$s = \frac{C}{\text{current density}}.$$

To satisfy this condition each feeder must be independently regulated by a battery, booster or separate 'bus bars at different pressures.

(2) Or, if all the feeders of different lengths are connected to one 'bus bar, and furnish the same pressures at the feeding points, there will be the same drop in each. The current densities will not be identical in all of them, but it is possible to find an average value for the drop of pressure, and hence for the current density, which will give the most economical results. For this purpose the expression for the total annual costs is written in terms of the drop v.

Annual losses $= (as + b)pl + \dfrac{C^2 Ipl}{Ks} + \dfrac{C^2 Ntl}{Ks}$, and by substituting $C = \dfrac{Kvs}{l}$ in that term of the expression for efficiency which has to be differentiated—*i.e.*,

$$(as + b)\frac{pl}{C} + \frac{CIpl}{Ks} + \frac{CNtl}{Ks} = (asl^2 + bl^2)\frac{p}{Kvs} + Ipv + Ntv = L$$

and $\Sigma_1^{\,n}$ (L) for n feeders $= \{a\Sigma(sl^2) + b\Sigma(l^2)\}\dfrac{p}{Kv\Sigma(s)} + Ipv + Ntv.$

Differentiating with respect to v and equating to zero,

$$\{a\Sigma(sl^2)+b\Sigma(l^2)\}\,p=v^2K\Sigma(s).\quad (Ip+Nt)$$

and average drop $\quad v_m=\dfrac{1}{K}\sqrt{\dfrac{apK}{Ip+Nt}\cdot\dfrac{\Sigma(sl^2)}{\Sigma(s)}+\dfrac{bpK}{Ip+Nt}\cdot\dfrac{\Sigma(l^2)}{\Sigma(s)}}.$

The value of v_m thus found would be the economical regulating voltage common to all the feeders, and the best current density for each is obtained from the formula $\dfrac{C}{s}=\dfrac{Kv_m}{l}$.

As already pointed out for a single feeder, the economy generally plays a secondary part to temperature rise, and the calculation of the average economic drop would be an unnecessary refinement in most cases.   In the various modifications of Kelvin's law the current density is always dependent on the square root of an expression embodying the economic factors of the station and feeders.   On this account its value changes slowly, even for a large change in any of the terms under the square root sign.   For example, if the price of copper should vary 50 per cent., the current density will not be affected by more than 20 per cent.

Special Cases of Maximum Efficiency of Transmission.

We have already dealt with the determination of the best current density for economy in the cases of (1) a definite power transmitted, (2) the utilisation of a cable already in operation on a growing system and (3) a group of feeders with common regulation.   The problem of maximum efficiency may also arise under numerous other aspects.

For instance, with a hydro-electric scheme furnishing its maximum possible power to a distant consumer at a contract price per kilowatt year, it is the best policy to fix the value of the losses in the line so that the profits on the capital invested are a maximum.

Let W_1=power generated,
$\quad$ A=cost of the plant and hydraulic works,
$\quad$ B=cost of the line without the conductors,
$\quad$ M=cost of the conductors,
$\quad$ D=total cost of working exclusive of those due to the conductors,
$\quad$ E=costs due to the conductors.

If P is the contract price per kilowatt year, and the power received is W_2, the gross income will be PW_2 and the net income

$$PW_2 - D - E.$$

The capital invested is $A + B + M$ and thus the percentage profit

$$= F = \frac{PW_2 - D - E}{A + B + M}. \qquad \cdots \cdots \quad (1)$$

We have now to find the value of the energy loss in the line to make F as high as possible.

It will be noticed that the period of use (N in Kelvin's law) does not affect this special case, since the charge is purely an annual rental. Obviously the investigation must take into account the maximum value of the power transmitted, so that as much as possible may be sold. To determine the line losses we must know the following quantities :—

a = percentage charges on the capital cost of the copper (interest, depreciation and repairs).

n = number of conductors (two for direct or single-phase and three for three-phase currents).

l = simple length of the line.

K = resistivity constant.

m = specific gravity of copper.

p = price per lb. of copper.

If c is the current per conductor and x is the percentage loss to be determined, the following relations hold good :—

$$\text{Power received} = W_2 = W_1 - xW_1 = W_1(1 - x) \quad \cdots \quad (2)$$

$$\text{Annual charges against the line} = E = aM \quad \cdots \cdots \quad (3)$$

$$\text{Cross-section of each conductor} = s = l \cdot \frac{nc^2}{KxW_1} \quad \cdots \quad (4)$$

$$\text{Cost of the conductors} = M = n^2 \frac{l^2}{K} \cdot m \cdot p \frac{c^2}{xW_1} \quad \cdots \quad (5)$$

All the quantities in (5) are constant except x, and thus it may be written $M = \dfrac{H}{x}$ and $E = a \dfrac{H}{x}$.

Substituting in (1)

$$F = \frac{PW_1(1-x) - D - a\dfrac{H}{x}}{A + B + \dfrac{H}{x}},$$

or

$$F = \frac{PW_1 x(1-x) - Dx - aH}{(A+B)x + H}.$$

Differentiating this expression with respect to x and equating to zero, we find the value of x which will render it a maximum is

$$x = -\frac{H}{A+B} \pm \sqrt{\frac{H^2}{(A+B)^2} + \frac{H\{PW_1 - D + a(A+B)\}}{(A+B)PW_1}} . \quad . \quad (6)$$

As a practical example of this formula we will take the case of $W_1 = 2{,}000$ kw. to be transmitted a length l, 50,000 yards at 20,000 volts, three phase, with a power factor $\cos \varphi = 0{\cdot}8$.

A+B at £40 per kilowatt=£80,000.

P the contract rate is £10 per kilowatt per annum.

D=£10,000 per annum (reckoning £5 per kilowatt working costs).

$a = 10$ per cent.

We first determine the cross-section s.

For a three-phase line (*see* Chap. X.)

$$s = \frac{l}{K} \cdot \frac{W_1}{V^2 x \cos^2 \varphi}$$

$$\begin{aligned} K &= 10{,}000 \\ V &= 20{,}000 \text{ volts} \\ \cos \varphi &= 0{\cdot}8 \end{aligned}$$

$$= \frac{50{,}000}{40{,}000} \cdot \frac{2{,}000 \times 1{,}000}{20{,}000 \times 20{,}000} \cdot \frac{1}{x \cos^2 \varphi}$$

$$= \frac{1}{160} \times \frac{1}{x \cos^2 \varphi} = \frac{1}{x} \cdot \frac{1}{160} \times \frac{100}{64} = \frac{0{\cdot}0097}{x}.$$

$M = nlmps$,

and $Mx = H = nlmpsx = nlmp \cdot 0{\cdot}0097$,

m = specific gravity of copper = 0·32 lb. per cubic inch,

p = price of copper = £0·05 per lb.

Thus H=3×50,000×36″×0·32×0·05×0·0097=844, and by inserting this value and that of the other factors in equation (6) we find x=8·75 (approx.)   The line loss for the given conditions to secure the best results is thus 8·75 per cent. of the power generated.

NOTE.—For a detailed account of this and similar problems *see* the Paper by Ing. G. Semenza in the " Proceedings," Assoc. Elett. Ital., January, 1903.

CHAPTER V.

SPECIAL TYPES AND ARRANGEMENTS OF FEEDERS.

Relative Merits of Boosted and Unboosted Feeders.

When certain feeders of a network are of exceptional length boosters are sometimes provided to compensate for their greater drop, and to permit of the use of only one pair of 'bus bars at the station, while still obtaining the best current density in each feeder.

Before deciding on this arrangement it is desirable to compare its efficiency with that obtained by increasing the cross-sections of the cables sufficiently to enable them to be run off the common 'bus bars at densities lower than the most economical. If C is the current to be transmitted by a feeder of length l that may require boosting, the economic drop $v_1 = \dfrac{l}{K} \times$ economic current density. The drop on the shorter feeders which determines the regulation on the 'bus bars is v_2.

Under these conditions the booster provides for power lost $= (v_1 - v_2)C$. The total annual costs with boosting are, therefore,

$$(as_1 + b)lp + (v_1 - v_2)CpT + ICv_1p + Cv_1Nt. \quad . \quad . \quad (1)$$

s_1 is the cross-section obtained from the "economic" formula, T is the capital cost per watt for the booster, and I, C, p, N and t have the same meanings as formerly.

If a heavy enough cable alone were employed its cross-section would have to be $s_2 = s_1 . \dfrac{v_1}{v_2}$, so that the drop in it might not exceed the regulating value v_2.

The total annual costs with the larger cable unboosted would be

$$\left(as_1\frac{v_1}{v_2} + b\right)lp + ICv_2p + Cv_2Nt. \quad . \quad . \quad (2)$$

If (1) $<$ (2) the system with boosters is the more economical. Simplifying this inequality,

$$(v_1-v_2)CpT+ICp(v_1-v_2)+NtC(v_1-v_2)\backsim \frac{1}{v_2} \cdot as_1(v_1-v_2)lp,$$

or $$CpT+ICp+NtC\backsim \frac{1}{v_2} \cdot as_1lp.$$

But $s_1=C\sqrt{\dfrac{Ip+Nt}{apK}}$ (from Kelvin's law), and by substitution

$$\frac{v_2}{apl}(pT+Ip+Nt)\backsim \sqrt{\frac{Ip+Nt}{apK}}. \quad . \quad . \quad . \quad . \quad (3)$$

Thus the expression on the left-hand side of the inequality must be less than the reciprocal of the economic current density from Kelvin's law if the booster alternative is to show an advantage.

A numerical example will indicate the scope of the formula.

With a declared pressure of 460 volts the regulating drop v_2 might be 40 volts. If a feeding point 1,500 yards from the station is being considered, $l=2\times 1,500=3,000$ yards, go and return.

$$a=16/8 \text{ per yard}=200 \text{ pence, } p=8 \text{ per cent.,}$$

while $(Ip+Nt)$ may be taken as $0\cdot 8$, the same as in the second example when working out current densities, and

$$\sqrt{\frac{Ip+Nt}{apK}}=\frac{0\cdot 9}{800}=0\ 0011.$$

The capital cost per kilowatt for a booster would be £10 approximately, or 2·4d. per watt. Thus

$$\frac{v_2}{apl}\{pT+(Ip+Nt)\}=\frac{40}{200\times \dfrac{8}{100}\times 3,000}\left(2\cdot 4\times \frac{8}{100}+0\cdot 8\right)=0\cdot 0008$$

This is less than the reciprocal of the current density (0·0011), and thus a booster would appear to be advantageous in this particular case.

The formula can be used to ascertain the critical length of a feeder beyond which boosting would be the more economical.

This length depends only on the quantities v_2 and a, apart from the factors which appear also in the statement of Kelvin's law.

It may be pointed out that the simplified formula (3) above is only approximately true. The annual cost per watt (t) of the power furnished by the booster has been taken to be identical with that of the power wasted in the cable itself. But, since the booster is driven by a motor with an average efficiency of about 0·75, the value of t ought strictly to be multiplied by 1·25 for that portion of the energy equal to $(v_1 - v_2)\mathrm{CN}$.

Furthermore, the reciprocal of the current density which appears in the right-hand side of the inequality ought properly to be derived from the second statement of Kelvin's law in which the cross-section is given and not the current. In point of fact this is the more reasonable aspect, as the feeder would probably have been in use some time before the question of boosting it, on account of increased load, had to be considered.

If it is desired to make the comparison with great exactness, the best plan is to obtain the numerical values of all the terms in (1) and (2), bearing in mind the two points just indicated. On taking the sum of each side it will be obvious which is the cheaper method of running.

The employment of boosters is not very popular, for various reasons As both positive and negative sides of the feeder on a three-wire system have to be dealt with by the booster, if symmetrical results are to be obtained at the feeding point, a machine with the necessary double armature and driving motor is somewhat unwieldy. A large number of them would therefore occupy too much floor space in the station, although several outlying feeders, when of approximately the same length, can all be boosted on the same machine and thus save space. The introduction of boosters is often indefinitely postponed, and heavy cables are used working at low-current densities for the sake of simplicity.

In general the necessity for extensive boosting is an indication that the limit of low-tension feeders has been reached, and, except for the desirability of retaining an uniformity of system, distribution at high tension would be preferable in such districts.

Special Cases of Boosting.

In the case of return currents for electric tramways the point of view is different. Here the conductivity of the rails is sufficient to convey the current back to the station from a considerable distance without requiring the use of feeders and without causing a drop in pressure that would be too uneconomical, but the prevention of electrolytic action in the neighbourhood of the track is a more cogent consideration than economy merely. To keep within the permissible limits of the B.O.T. on large systems, return feeders and so-called " negative " boosters have to be employed. Their function is to ensure such a voltage at the feeding points that the difference of potential between any two points of the rails does not exceed 7 volts.

One method of determining the best positions of the return feeders has already been discussed. When this has been done the total amount of current collected by each feeder can be found. As the length is known the drop in voltage v_f without boosting would be $v_f = \dfrac{l}{K} \cdot \dfrac{C}{s}$, the symbols having their former meanings.

But if the negative pole of the generators is earthed at the station this implies that $v_f + v_d = v$, where v_d is the drop in the track from any feeding point midway to the next, and v is the maximum total drop of 7 volts. In consequence of the small drop, v_f, the return feeder is practically an elastic conductor and therefore must have a very heavy cross-section.

The only alternative to obviate the use of heavy and costly feeder cables is the employment of negative boosters with cables of much smaller cross-section. That this is absolutely necessary, for economy can be realised by an examination of the formula (3) above, in which, if v_2 is very small (as in the present instance), the advantage of the booster is overwhelming. Thus the principle of comparative economy is identical, whether for the positive line feeders or for the track feeders. The effect of the booster in modifying what would otherwise be an excessive cross-section is the same in both cases, and any want of clearness attaching to this subject is mostly due to the expression " negative booster." This appellation might be

more strictly given to a machine inserted in an exceptionally short feeder in which the drop would be naturally too small compared with that in the other feeders.

The connections of the machine might be such that it acted as a motor driving a generator and returning power to the station, instead of having the extra voltage wasted in resistance, as is sometimes done in similar cases to ensure the proper pressure at the feeding point.

For economy of running in lighting systems it is usually preferable to make the regulating voltage depend on the shorter feeders, and to boost the longer ones, either by means of special machines or the utilisation of a portion of the generating plant coupled to 'bus bars at higher pressures.

In certain cases, with one or two extremely short feeders, it may be more economical to introduce resistances for regulation purposes to obviate the use of boosters. The relative merits of the alternatives could only be settled by the summation of the items of cost and noting which was smallest, just as in the case already considered of a partially boosted system.

One point to be observed, where there is a great discrepancy in the lengths of feeders supplying an interconnected network, is the current density in the short ones. These may very easily become overloaded if only one 'bus-bar pressure is available and thus necessitate the use of resistances or boosters for that reason alone.

In general, apart from questions of regulation or current density, the greater the amount of the load that can be dealt with by the short feeders the less will be the amount of copper required in the feeder system. (*See* Chap. III.).

Boosting without Feeders.   Tramway Return Feeders.

An example of boosting in a limiting case is the method suggested by Kapp (*E.T.Z.*, 1902, No. 1) for minimising the difference of potential between tramway rails and earth. Return feeders are dispensed with entirely, the fall of potential being compensated for by a single booster at the station end, or in the case of lengthy tracks by the introduction of boosters between each of the isolated sections into which the rails are electrically subdivided. If the cars are assumed to be distributed uniformly, the curve of fall of potential (Fig. 20), as already proved, will be a parabola, S being the central

station. If, now, the height of the furthest ordinate represents 9 volts and a booster is connected between the end of the track at S and earth, the differences of potential will be readjusted, as shown in Fig. 21. The P.D. between S and E should be 6 volts and that between K and E 3 volts, the area intercepted between the curve and EE, above and below that line then being equal.
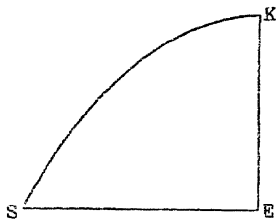
FIG. 20
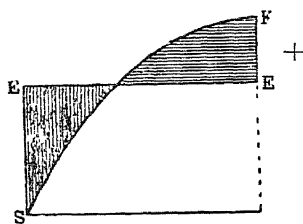
FIG. 21.

This is an instance of the employment of a booster on a feeder, the length of which is zero. The alternative of employing an unboosted feeder at a considerable distance from S, would certainly be less economical. It is immaterial whether the potential of the rails is positive or negative to earth so long as it is less than 7 volts. The only consequence of the sign of the potential is that in one case the electrolytic action
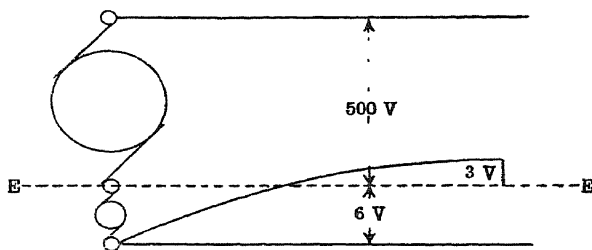
FIG. 22.

will tend to corrode the rails and in the other the water and gas pipes. The position of EE is such that the integrals of the two effects are equal and the possible damage is shared equally by the rails and the neighbouring pipes.

The booster system without return feeder can be considered as an example of a three-wire system of which the trolley line

E 2

and the rails are the outer conductors and the earth the neutral, while the pressures on the two sides are very unequal. This method of negative boosting of tramway systems to avoid electrolytic action does not entail much loss in distribution as can be recognised by regarding it as a three-wire arrangement (Fig. 22). The six volts added to control the potential of the rails relative to earth are available in furnishing that much higher working voltage to the car motors ; on the other hand it will be evident that the power required to boost long feeders on the positive side is a real distribution loss.

With insulated return feeders, singly or in groups, connected through boosters, the E M.F. furnished by the machines may, and should, be much higher than 6 volts. The greater the boosting E.M.F. the less will be the cross-sections of the return feeders. The loss in such cases is the product of the E.M.F. of the booster and the current it deals with.

Examples on Tramway Feeders.

Illustrating the principles just outlined we give some calculations for a double tramway track with 100 lb. rails, and a loading of six cars per mile, each taking 20 amps.

Dealing with copper resistance we had $r = \dfrac{L}{Ks}$, where K was 40,000 with L in yards and s in sq. ins   (K is 22 7 with L in miles and s in sq. ins.).

For tramway problems one mile is the better unit, and thus we have for steel rails $r = \dfrac{L}{K_1 s}$ where K_1 is the constant for steel resistance, L is in miles and s in sq. in.

The relative resistivities of copper and steel are 0·64 and 7·4 microhms per cubic inch respectively, and thus we find $K_1 = 1·96$.

The cross-section of a 100 lb. rail is very nearly 10 sq. inches, so that the four rails of the track, when bonded together, give a total cross-section of 40 sq. in.

1. To find the voltage drop in the rails we have the general formula $v = \frac{1}{2} \dfrac{C_0 L^2}{K_s}$ where C_0 is the uniform load tapped off per unit length.

For the steel track $v = \frac{1}{2} \dfrac{C_0 L^2}{K_1 s}$,

where
$$C_0 = \text{amps. per mile} = 120,$$
$$L = \text{length in miles,}$$
$$K_1 = 1·96,$$
$$s = \text{cross-section} = 40 \text{ sq. in.}$$

When the length is only one mile from the works or sub-station feeding the-track,

$$v=\frac{\frac{1}{2}\times 120\times 1^2}{1\cdot 96\times 40}=0\cdot 76 \text{ volts}$$

From the parabolic law (*see* Chap. III.), $v=$const.$\times L^2$, we see that a two-mile track would give $4\times 0\cdot 76=3\cdot 04$, three miles $9\times 0\cdot 76=6\cdot 84$, and four miles, $16\times 0\cdot 76=12\cdot 16$ volts.

The limiting voltage drop being 7 volts (B.O.T. regulation) it is necessary to have a negative feeder for any length of track exceeding $3\cdot 07$ miles. But there is another B.O.T. regulation fixing the maximum current density at 9 amps. per sq in., so that 360 amps. $(=9\times 40$ sq. in.) is the limit for any part of the track as a simple conductor. The current at the supply end of a three-mile length is 3×120 amps.$=360$ amps., and for this reason the track, without a feeder, should not exceed 3 miles. In all problems of this kind, even when the drop is right, the current density must also be watched.
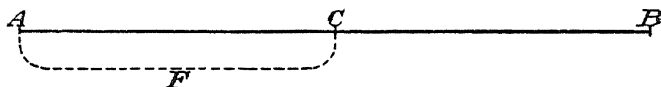
FIG. 23.

2. Suppose a feeder run parallel to the track from the station at A to C two miles distant. The drop from C to B is, as shown above, 3 04 volts. Keeping within 7 volts this leaves $7-3\cdot 04=3\cdot 96$ volts available between C and A. The drop in AC due to its load currents is also 3 04 volts, leaving a balance of $3\cdot 96-3\cdot 04=0\cdot 92$.

From this we can find the part of the load of CB it will carry back to A.

$$v=\frac{CL}{K_1 s} \qquad \left\{ \begin{array}{l} v=0\ 92 \\ L=2 \text{ miles} \\ K_1=1\cdot 96 \\ s=40 \end{array} \right.$$

Hence the current

$$C=\frac{0\cdot 92\times 1\cdot 96\times 40}{2}=36 \text{ amps.}$$

The load on $CB=2\times 120=240$ amps, and thus the balance to be conveyed back by the copper in the feeder F is $240-36=204$ amps. The drop from A to C is $3\cdot 96$ and, if C_f is the current in the feeder the cross-section $s=\dfrac{C_f L}{Kv}=\dfrac{204\times 2}{22\cdot 7\times 3\cdot 96}=4\cdot 53$ sq. in.

This involves too much copper for economy, confirming what we have already seen regarding unboosted negative feeders generally.

There is no cutting point in AC under the conditions shown, as the track and the feeder are working in parallel between A and C, and the current flow is all in one direction from B to C and A.

3. Suppose now we have a negative booster in the feeder circuit, generating an E.M F. of 50 volts to compensate for the drop in a cable of reasonable size, the cross-section of this cable would be

$$s = \frac{C_f L}{Kv} = \frac{204 \times 2}{22 \cdot 7 \times 50} = 0 \cdot 36 \text{ sq. m.}$$

The advantage of this arrangement is obvious at once.

Trunk Feeders and Bunched Feeders.

Where a heavily loaded district is situated at a considerable distance from the central station, and is extensive enough to require several feeders, it may happen that these will run along the same route for a great part of their length. Considerations of economy would in such a case point to the advisability of replacing the individual cables, which run in a common trench, by a single trunk feeder. From the end of this the various sub-feeders branch to the feeding points of the network. Such an arrangement is practicable only when the branch feeders diverge to about the same distance from the common end of the trunk feeder. Otherwise it would be quite impossible to regulate the pressures at the feeding points, that is, assuming they all work at the same current density which also satisfies Kelvin's law. There is a saving with a trunk feeder, although it may have a cross-section equal to the sum of all the cables it replaces, because the cost, represented by the b term in the expression $(as + b)l$, and the cost of laying are very much reduced.

If the characters of the loads in the districts fed by the sub-feeders are such that their peaks are non-coincident, their diversity factor can be allowed for in estimating the total load on the trunk feeder and its cross-section can be correspondingly less. If it is thought unwise to cut down the cross-section so closely, the existence of the diversity factor will contribute to the elasticity of the feeding system and will materially improve the regulation.   There is evidently a diminished security by substituting a trunk feeder for the separate cables, and it may hardly be considered worth the risk to employ one cable only. The benefits of the diversity factor will still be available, however, if the separate cables are all coupled together in a disconnecting box or feeder pillar at the point of divergence. If a fault occurs on any one of them between this point and the station it can be easily disconnected

and the remaining cables will take the load. With such an arrangement the highest degree of safety is attained together with an efficient utilisation of the whole of the conductors laid down.

Design of Split Feeders.

Assuming that the comparison of the relative merits of economy and security indicates that the latter would not be seriously prejudiced, it then becomes necessary to choose correctly the cross-sections of the trunk feeder and its branches. The average current density in the branches is obtained from the formula already established for several feeders of different lengths and supplied from the same source, which in this case is represented by the common end B of the trunk main, instead of a central station.
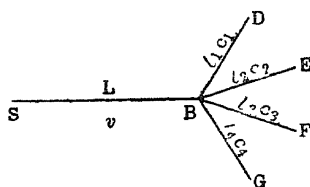
FIG. 24.

The current density in SB (Fig. 24) is obtained from the ordinary statement of Kelvin's law. If C_1, C_2, C_3, &c., are the loads on the various branches, the cross-section of SB is equal to

$$s_1 = \frac{\Sigma_1^n(C)}{\text{current density}}.$$

It occasionally may happen that the problem presents itself in the form of determining the cross-sections of the main and sub-feeders under the condition that the total drop V must not exceed a definite figure, in order to ensure simplicity of pressure regulation. Under the circumstances, if v is the drop in SB and $V-v$ the drop in any one of the branches, then the cross-section of $SB = s = \dfrac{L \cdot \Sigma_1^n(C)}{Kv}$, and the cross-section of

any branch $= s_n = \dfrac{l_n C_n}{K(V-v)}$.

The best apportionment of the total drop is such that the volume of copper in the set of cables is a minimum.

$$\text{Volume of copper} = Q = sL + \Sigma_1{}^n(s_n l_n)$$

$$= \frac{L^2 \Sigma_1{}^n(C)}{Kv} + \frac{\Sigma_1{}^n(l_n{}^2 C_n)}{K(V-v)}.$$

If this expression be differentiated with respect to v and equated to zero, we have the following equation giving the best value of v:—

$$\frac{v}{V-v} = \sqrt{\frac{L^2 \Sigma_1{}^n(C_n)}{\Sigma_1{}^n(l_n{}^2 C_n)}}.$$

When the branches are all of practically the same length, or l_n is the same for each, then the total drop is subdivided in the ratio $\dfrac{v}{V-v} = \dfrac{L}{l_n}$, and $s = \Sigma_1{}^n(s_n)$, or the cross-section of the main must be equal to the sum of all the branches radiating from B.

As an example suppose L to be 1,000 yards feeding three branches: (1) 300 yds. with load of 100 amps., (2) 400 yds. with load 60 amps., and (3) 500 yds. with load 20 amps.

Then

$$\Sigma_1{}^n C_n = 100 + 60 + 20 = 180$$

and

$$L^2 \Sigma_1{}^n C_n = 1,000^2 \times 180 = 180,000,000,$$

$$\Sigma_1{}^n(l_n{}^2 C_n) = 9,000,000 + 9,600,000 + 5,000,000$$

$$\sqrt{\frac{L^2 \Sigma_1{}^n(C_n)}{\Sigma_1{}^n(l_n{}^2 C_n)}} = \sqrt{\frac{1,800}{236}} = 2 \cdot 76 = \frac{v}{V-v},$$

or the drop in L is 2·76 times that in the branches. If all the lengths were equal, say, 400 yds. (the average of the three), $\dfrac{v}{V-v} = \dfrac{1,000}{400} = 2 \cdot 5.$

Under practical conditions, and bearing in mind the desirability of having the branches all of approximately the same length, the rule, in the case where the total drop V is given, would be to subdivide it in direct proportion to the respective lengths of the main and branch. As already hinted, however, if there is a marked diversity factor amongst the districts fed by the branches, allowance may be made for it, and s may be correspondingly less than $\Sigma_1{}^n(s_n)$.

Advantages and Disadvantages of Split Feeders.

Considerable stress should be laid on the necessity for having the branches all of the same length when a " split " feeder is used, otherwise great trouble with pressure regulation is likely to be met with.

For instance, with the portion of network shown in Fig. 25 consisting of a long, narrow district situated at a great distance from the station S, it is inadvisable to feed first at F_1 and then prolong the feeder to F_2. Under the exigencies of pressure regulation, the P.D. between F_1 and F_2 ought not to exceed approximately $1\frac{1}{2}$ per cent. of the declared pressure. This implies that the part of the feeder between F_1 and F_2 would be running under precisely the same conditions respecting drop in pressure as the distributor, with which it is, in fact, working in parallel. In designing this part of the network originally it would, therefore, be equally good for regulation, and ob-
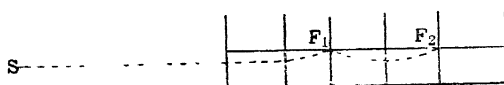
FIG. 25

viously much cheaper, to put the extra copper of the feeder extension into the distributor, and to choose a single feeding point between F_1 and F_2.

It does not require elaborate calculation to ascertain, by the methods already given, whether, in the case of a long straggling district, one or two feeding points would give the cheaper result, *inclusive of distributors.* If, however, a split feeder is being discussed for a district where distributors are already laid, and if the only alternative is to have the extension tail running along the same route as the distributor, it is then imperative to treat the extension as working in parallel with the latter. It must, therefore, have a much greater cross-section, or run at a lower current density, than if it were taking its proportionate drop working as a true feeder.

Against the alternative of running two separate feeders right back to the station, it can be readily verified which is the cheaper in capital outlay. There is one other arrangement open to the designer, and that is to have the pressure regulated

on the more remote of the two points. This permits the employment of a higher current density, and, therefore, a smaller cross-section of conductor on the extension ; but the pressure at the nearer of the two points will be too high, and necessitate the introduction of a resistance there to lower it to the network value. Apart from the loss naturally entailed by the use of resistances, there is the difficulty of their satisfactory disposal and housing. It is, therefore, inadvisable to adopt the resistance method, unless the smallness of the cross-section of the distributors already in existence practically precludes any other. If two separate feeders are employed, it will be observed that the total cost is not very much higher than with a split feeder, the cross-section of which, up to the point of partition, would be equal to the sum of the two former.

The expression $(as+b)l$ represents the cost of the single split feeder, inclusive of laying, and $2\left(a \cdot \dfrac{s}{2}+b'\right)l=(as+2b')l$ the cost of the two separate ones. But, as they are both laid in the same trench, $2b'l$ will be less than $2bl$, and thus the difference in cost of the two systems, due only to the b terms, may be very small. It must be remembered, further, with the split feeder that its prolongation means extra copper, on account of its being virtually a parallel distributor, and thus $a \cdot s \cdot$ in the one case will be greater than $2 \cdot a \cdot \dfrac{s}{2}$ in the other. On balance, therefore, there would not be much against the two separate feeders, especially as the distributing system would be lighter than with a single feeder. If this method be selected, the load should be divided between the two, so that their cutting point satisfies the equation

$$L^2=\frac{v}{V}\left(D_1{}^2-D_2{}^2\right).$$

The position of the cutting point found in this way will probably be fairly close up to F_2. Should D_1 and D_2 differ widely in length, and the cables are both run at the mean current density derived from Kelvin's law, the drops will be different. If the drop in each feeder is the same—*i.e.*, V—the current densities in each will be different ; but they may be so adjusted that their mean approximates to the theoretical economic value.

Example of the Use of Split Feeders.

As an illustration of the difficulties met with in the employment of split feeders, some particulars are appended of a district fed in this manner in one of the south-coast towns (Fig. 26). When the network was being projected for this district it was considered more economical to lay a 0·8 in. feeder to F_1 (a distance of about a mile from the station) and to add an extension of 0·6 in. area split off the same feeder to the point F_2, a distance of about 600 yds., instead of laying a second independent feeder to supply the district round F_2 and beyond. Pilot wires were led back from F_1 and F_2 so that the pressure variations could be observed at both points.

As the number of consumers increased complaints of bad pressure were numerous, and at times of full load it soon
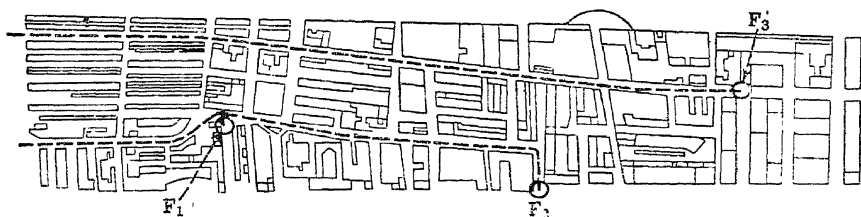
Fig. 26

became evident that the system was far from being self-regulating. The load on F_2, which was mainly residential, was greater than had been anticipated, and it followed a very different load curve to that of F_1, which supplied a large proportion of shops. Thus, at certain times in the evening, there would be a variation of 10-15 volts in 460 between F_1 and F_2. The only remedy was to insert resistances at F_1 and to regulate on the mean value of the voltages at F_1 and F_2. This makeshift arrangement lasted for a year or two, but no permanent satisfaction was obtained until a 1 sq. in. feeder about $1\frac{1}{2}$ miles long had been laid direct to the point F_3. The old split feeder is now used as a distributor, and does good service in extending the natural and proper feeding area of F_1, leaving F_3 to do but little feeding backwards, in accordance with the formula $L^2 = \dfrac{v}{V}(D_1{}^2 - D_2{}^2)$.

The principal reason why this district is so awkward to deal with is on account of its being practically isolated from the rest of the network, and getting no assistance from any of the other feeders.   It is bounded on the south side by the sea and on the north by unoccupied land, its length being about 1,300 yds. and its width 300.   The remoteness and isolation demanded special treatment, but in all probability split feeding was not the best under the circumstances, as there are now 600 yds. of 0·6 main being used inefficiently.

Equalising Mains and Their Design.

The function of the extended branch of a split feeder of the type just described closely resembles that of an equalising main.   With an inter-connected network and a common regulation for all the feeders there are usually equalising currents in the distributors.   This may be due to an unexpected
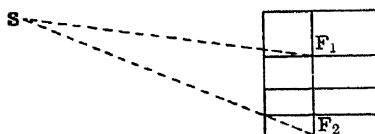
FIG. 27.

shifting of the load centres after the feeders have been laid, or it may be the result of want of care originally in the design of the system as a whole.

When certain districts are subject to great fluctuations in the relative incidence of their loads, the use of equalising mains is not only a legitimate but a necessary device, always assuming that the feeders are required to be run from the same 'bus bars and that their areas are inter-connected.

For instance, if F_1 and F_2 (Fig. 27) are two feeding points, and it is found that the pressure at F_2, on account of its heavier load or greater length, is too low in comparison with F_1, some arrangement must be made to cope with these conditions. To lay additional copper to F_2 may be too costly or inconvenient ; but one way of making the necessary correction is to have a heavy conductor joining up the two points.   This may either be a special main, to which no consumers are connected, or the ordinary distributor may be made heavy enough to

perform this additional duty. In either case the length of main from F_1 to F_2, in so far as it supplies current to F_2 or encroaches upon its natural feeding area, is virtually the extension of the feeder SF_1, which splits at F_1, and the arrangement carries with it all the drawbacks already referred to with split feeders in general. To fulfil its purpose the current supplied through the equalising main from the point of higher to that of lower pressure must not cause a drop in volts exceeding a small percentage of the declared pressure at the consumer's terminals.

To take a simple example · CA and CB (Fig. 28) are two feeders of resistance r_1 and r_2, and carrying a load of C_1 and C_2 respectively. The drop at B due to the load C_2 is excessive, and it is necessary to transfer a portion of it (x) to the feeding point at A, and to make AB of such a resistance as to ensure this.
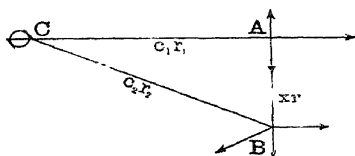
FIG. 28.

If the current in AB is x and its resistance r, then, applying Kirchoff's law to the triangle CAB, after the feeder loads take their new values,

$$(C_1+x)r_1+xr=(C_2-x)r_2.$$

The relation of x to r is determined by the fact that the drop v in AB is known, for it must not exceed, say, 2½ per cent. of the supply voltage, and, as $x=\dfrac{v}{r}$, by substitution

$$r=v \cdot \frac{r_1+r_2}{C_2r_2-C_1r_1-v},$$

and if the length of AB is l and cross-section s, $r=\dfrac{l}{Ks}$,

or

$$s=\frac{l}{Kr}=\frac{l}{Kv} \cdot \frac{C_2r_2-C_1r_1-v}{r_1+r_2}.$$

The above equation determines the size of AB when it is a special main, but if, on the other hand, it is the ordinary distributor supplying consumers, it must be correspondingly larger.

The principle of the super-position of currents already referred to enables these consumers' loads to be considered separately (Fig. 29). The position of the resultant current $C = \Sigma(c)$ is first found—*i.e.*, so that

$$R_1 = \frac{\Sigma_1''(Cr)}{\Sigma_1''(c)} = \frac{\Sigma_1''(cr)}{C}.$$

The resultant current C can be analysed into two components acting at A and B respectively, thus freeing AB from the consumers' currents.
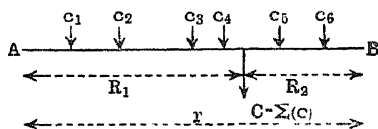
FIG. 29.

The component of C acting at $A = C \cdot \dfrac{R_2}{r} = p_1 C$, and the component at $B = C \cdot \dfrac{R_1}{r} = p_2 C$. Adding these to the former values of C_1 and C_2 and substituting, the expression for s becomes

$$s = \frac{l}{Kv} \cdot \frac{(C_2 + p_2 C)r_2 - (C_1 + p_1 C)r_1 - v}{r_1 + r_2}.$$

If the feeding points are connected by a complex network with several paths in parallel, as usually happens, it is impossible to establish such a simple relation between the resistances of the equalising mains and the feeders.

These conditions can, however, be treated by the employment of the general methods of analysing networks given later. At the best, the calculated result is only approximate, as any readjustment of the load between any two feeders makes its influence felt throughout the whole of the feeding system.

Although true theoretically, this effect is scarcely noticeable on the remoter feeders, and the above method is sufficient practically for indicating how to equalise pressures by considering only the two feeders immediately concerned.

Examples of Equalising Mains.

The following examples show quantitatively the influence of an equalising main :—

In Fig. 28, CB is 1,500 yds. long and 0·3 cross-section ; thus $r_2 = 0·25$ ohms for the forward and return conductors.

CA is 1,000 yds. of 0·25 cross-section with $r_1 = 0·2$ ohms.

AB is 400 yds. and the loads at A and B, before being interconnected, are $C_1 = 160$ amps and $C_2 = 300$ amps

In laying the cable A to B it is found that a total consumer's load of 120 amps. can be secured. This is distributed along the route, but the resultant current is such that R_1 is 300 yds and R_2 100 yds. Thus p_2C is $\frac{300}{400} \times 120 = 90$ amps and $p_1C = 30$ amps.

The difference of pressure between A and B is limited to 3 per cent. of the declared voltage of 250 two wire . or $v = 7·5$ volts

Then
$$s = \frac{l}{Kv} \cdot \frac{(C_2 + p_2C)r_2 - (C_1 + p_1C)r_1 - v}{r_1 + r_2}$$

$$= \frac{800}{40,000 \times 7·5} \cdot \frac{(300 + 90)0·25 - (160 + 30)0·2 - 7·5}{0·2 + 0·25}$$

$$= 0·31 \text{ sq. in. } . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If there are no consumers' loads on AB and it is used solely as an equaliser, the terms p_2C and p_1C disappear, and we find from the simpler formula

$$s = 0·21 \text{ sq. in. } . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

In example (1) current flowing through AB towards B is x, and

$$x = \frac{v}{r} + C \cdot \frac{R_2}{r} = \frac{v}{r} + p_1C$$

For the 0 31 two wire main 400 yds. long $r = 0 064$ ohms ; hence $x = \frac{7·5}{0 064} + 30 = 147$ amps. The load C takes 120 amps., leaving 27 to go on to B.

The total current in the feeder CA now becomes $160 + 147 = 307$ amps., and in CB $300 - 27 = 273$ amps.

In example (2), with no consumers' loads on AB $x = \frac{v}{r}$ simply, and, as r for the 0·21 main is 0·095 ohms, $x = \frac{7·5}{0·095} = 79$ amps. The whole of this current flows to B, diminishing correspondingly the load on the feeder CB, which now becomes 221 amps., while that on CA becomes 239 amps.

Utility of Equalising Mains.

The utility of an equalising main is well illustrated in the following example. This is in a seaside town which is divided into two parts by a tidal river, the area fed by F_1 and F_2 (Fig. 30) being the more populous and rich, and, consequently, giving a much heavier load on the feeders than the district fed by F_3 and F_4. The loads on the latter were, in fact, so small that it was necessary to insert resistances in them, the station being of modest size and possessing only one pair of 'bus bars.
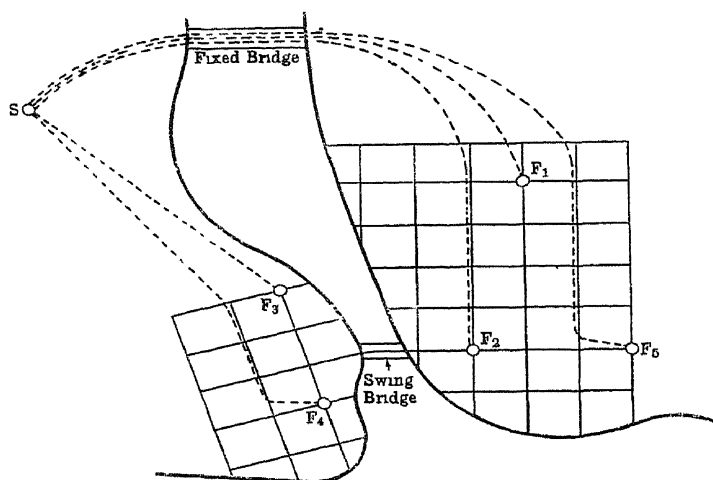
FIG. 30.

The difficulty of regulating had increased to such an extent as to render it advisable to consider laying down another feeder for the denser area, but the alternative of employing an equalising main between the two districts hitherto cut off from each other was soon found to be the cheaper, even although it involved the laying of a submarine cable close to the swing bridge at the narrow part of the river.

The arrangement operates beneficially in two ways, firstly, by relieving F_1 and F_2 of a part of their loads, and secondly, by transferring enough additional load to F_3 and F_4 to avoid the use of resistances in them, and simplifying the whole regulation of the network. The formula for calculating the

resistance of the equalising conductor is directly applicable here, by assuming the alternative paths as the means of the lengths to F_1 and F_2 and to F_3 and F_4 respectively. It is seldom in practice, however, that such a simple case of equalising two isolated networks is met with.

Practical Considerations affecting the Position of Feeding Points, &c.

As already shown, the determination of feeding points from a general mathematical expression is only possible when the load per unit of area is uniform, and when the area can be split up into simple geometrical shapes such as circular zones and sectors. An ordinary network is too complex and the distribution of the load too irregular to permit of any universal analytical treatment; in the practical lay-out of feeders experience demands that certain conditions be fulfilled, which may modify considerably the theoretical arguments. The following are points which usually influence the design.

The ground plan of the streets is the chief limitation in laying out a distribution scheme, with buried cables, as the latter must necessarily follow the same plan. The feeders should run by the shortest street routes to the centres of heavy load, and preferably to points where several streets intersect so that as many distributors as possible may be fed directly and thus minimize the drop in pressure and the weight of copper.

If the feeders cannot all be made of about the same length owing to the configuration of the area and the position of the supply station, they should be arranged so that they form groups in each of which the average length is the same so as to facilitate regulation from different 'bus bars.

The cutting points between adjacent feeders having been determined so as to give minimum capital cost of copper in the system, the loads and cross-sections of each feeder can also be found. Several trial calculations with various numbers of feeders must be made, however, before settling on the final arrangement, using the principle already referred to, *i.e.*, that with numerous feeders the distributors are lighter and with few feeders they are correspondingly heavier. A minimum investment can thus be determined, and the positions of the feeding points corresponding to this should be fixed upon as far as possible.

The great consideration underlying this method of design is that of providing for the *full-load* development of the district. In practice the distributors when once laid cannot easily be disturbed, and this introduces a material difficulty. If their sections are chosen for ultimate requirements they will be much too large in the earlier stages, and it may be more advantageous for the undertaking to depart from the calculated values and lay smaller mains, at least in the outlying districts. In this way less capital is required and the annual charges are lower during the first years, when the business is struggling. There is no difficulty with the feeders, as in any case they would only be laid as required by the growth of the load. Probably a compromise between the two alternatives is desirable, so that in the final state of the network the feeders are rather more numerous and the distributors lighter than if the theory alone were strictly followed.

As the distance from the station increases, the cost of an additional feeder will be more serious, and thus it is desirable to exercise great care initially in designing the system so as to avoid having to apply this expensive correction at a later date. Much economy can be achieved by the judicious use of trunk and bunched feeders run to the centres of well-defined areas, where they are split into subsidiary feeders. The further away the district is from the station the higher will be the economy of this method ; it entails little risk of breakdown, and has no other disadvantages, if precautions are taken to ensure proper voltage regulation.

An excellent system has been adopted by one of the large English companies controlling numerous small undertakings. The feeders and network are first calculated for the probable final loads but only a few of the light feeders are laid to commence with In subsequent years, as necessity arises, the heavy ones are added. Thus in time a thoroughly consistent system is evolved, without saddling the undertaking with heavy and unproductive capital charges in the early years.

Separation of Feeder Districts.

For supply systems in large cities, owing to the serious breakdowns which have occasionally taken place when the distributors were all interconnected, the best practice is to divide up the area into sections corresponding to the feeders. This

method is the subject of one of the B.O.T. Regulations, which requires fuse pillars or street boxes to be employed at the points where the feeder areas interconnect, the fuses being heavy, enough merely to carry the slight equalising currents due to the fluctuations in the relative loads. Should a bad fault occur in one feeder area the fuses will blow and automatically isolate it without disturbing the rest of the network. The correct positions of these fuse pillars can be arrived at when the system is being designed by the rules already prescribed (*see* Chapter III.), but for existing feeding points when the loads have reached a comparatively steady state they may be ascertained experimentally. The method adopted with a draw-in system is to place a compass on the distributors in various inspection pits at the time of full-load, and to note from the change in the direction of the deflection where the current begins to be supplied from the next feeder It is instructive to compare the positions of the cutting points thus found with those calculated from the formula. For permanent safety in running much is to be said for keeping each feeder area quite separate and supplying it from one feeder only, each distributor also being usually fed from one end only This arrangement has been adopted in Glasgow, and appears to give good results on large networks.

For traction systems it has much to recommend it. In THE ELECTRICIAN, Vol. LVIII., pp. 19 and 219, the arguments in favour of its adoption are fully discussed.

The regulation, when unconnected feeder areas are employed, must be made with some nicety on lighting systems. By properly grouping them according to length on separate portions of the station plant the feeding-point pressures can be kept within close limits. This alone is insufficient, however, and careful calculations must be made of the respective drops in the radiating distributors, as the consumers on the confines of the area can receive no assistance from neighbouring areas through equalising mains. The proper balancing of the two sides with three-wire working must be rigorously made on each and every main, as the want of an elastic network is felt most of all in connection with " balancing," although the feeders may all have a third wire back to the station.

Several advantages in addition to security characterise this method of unconnected feeding areas. The first is that the

distributors can be fed in any direction to exactly the distance corresponding to the formula for the minimum weight of copper.   If the loads have reached their limits or their possible values are ascertainable the cross-sections of the distributors can be fixed accordingly.   There being no excess of elasticity in the mains under these conditions there is obviously no super-fluous copper.

The second advantage is that each supply area being inde-pendent, there is no need for network analysis or discussing any of the complications of equalising mains, split feeders, &c. The third advantage is that the maximum load on the feeders is directly given by adding those of all the radiating distri-butors.   These attributes which facilitate design are not, perhaps, the principal merit of the method, that being the restriction of the area which can possibly be affected by any fault.

Each distributor being fused in the feeder pillar the fault usually locates itself by blowing one of these fuses and isolating the faulty main.   By means of the section pillars provided at the cutting points, supply can be given in emergencies from another feeder by inserting the fuses which are normally not in use.

How the Network influences Pressure Regulation.

The maintenance of an uniform pressure at the consumer's premises from hour to hour is mainly a question of station operation, but a great deal of its success depends on the arrangement and design of the external distribution system. The fluctuations in the load, as represented by the daily load curve, would hardly affect the mains engineers' department if there were no diversity in their relative incidence in different districts.

The following is a short *résumé* of how the distributing system influences the problem of regulation.   Some of the points have already been referred to at some length :—

Taking first the small two-wire station with only one pair of 'bus bars, it is evident that the regulating voltage ought to be the mean of the values of all the readings of the feeder volt-meters.   This simple arrangement implies that the system must possess a good deal of elasticity and that either the feeders must all be of approximately the same length or they

must be closely interconnected by a sufficiently heavy network. The longer feeders then take proportionately less load and work at less than maximum economy as the current density is below the normal. If one or two are exceptionately long they must be boosted to the proper amount or they may receive assistance from the others through equalising mains. As the B.O.T. regulation for declared pressure permits a total variation of 4 per cent. up or down the maintenance of a satisfactory pressure at consumers' terminals is assisted, if the feeding points are run at an average of 4 per cent. *higher* than the declared value. If the distributors are designed for a 3 per cent. drop it is then practically certain that there will be no abnormally low pressure at consumers' terminals.

Exceptionally short feeders should be avoided, but if that is impossible their voltage must be adjusted by resistances in series. Wasteful as this method inherently is there are some cases in which it is admissible.

For a small station either or both of these methods may be preferable to running on several 'bus-bars at different pressures. This necessitates the setting aside of distinct portions of the plant for the different bars, and may cause the plant load-factor to show a poor value, as it practically amounts to running on separate circuits instead of in parallel.

With large stations this argument no longer applies, as each bar will relatively have a substantial load, and the plant load-factor on the whole station will not be affected. This is, therefore, the customary method, the feeders being grouped on the various bars in accordance with their respective lengths. The current density derived from Kelvin's law or the maximum value allowed by temperature rise can then approximately be employed for every feeder.

The network is usually linked up as closely as possible with any of the above systems, but if it should happen that the shopping, residential and industrial areas are separate and well defined, the elasticity of the network will be insufficient to nullify the effect of their diversity factor. Where several 'bus-bars are available it may be necessary to shift some of the feeders from one bar to another during the evening as the peak in each district increases or diminishes.

Again, in towns where the central load is mostly that of shops while that of the external zone is residential, a number

of the short central feeders (working off one pair of 'bus-bars only) must be disconnected after closing time and the whole network fed through the longer feeders, thus increasing the distance between the feeding points for the time being and rendering the pressure more uniform throughout.

These alternatives refer only to interconnected networks. Where the feeders supply independent areas, special precautions must be taken as already described. Where bunched or split feeders are used the extension pieces beyond the point of partition must be made self-regulating, it being impossible to effect any general control from the central station beyond that point.

It is remarkable how close the regulation may be in some cases even with only one pair of 'bus-bars, and a great disparity in the lengths of the feeders. Such temporarily good results are entirely due to the relatively small loads on the longer feeders, or the excessive weight of copper in them. In the long run, with a fully developed load, the question of combining efficient regulation with an economical outlay in cables has to be thoroughly treated.

For three-wire and low-tension polyphase systems with or without neutral wires the effect of " balancing " in regulation is of paramount importance. Means for ensuring good balance are considered fully in the section relating to the various systems of distribution.

CHAPTER VI.

THE HEATING OF CABLES.

General Effects of Heating Losses.

In every cable used for electrical distribution some of the energy transmitted is converted into heat, the rate of conversion being proportional to C^2R, where C is the current (supposed uniform) and R is the resistance. This transmission loss is largely unavoidable, but it must be kept within definite limits for several reasons.

In the first place, the resistance of the cable increases with the rise in temperature—0·4 per cent for 1°C., or 10 per cent. for a total rise of 25°C. The drop in pressure is affected in the same proportion, and in the case of a 25 deg. rise, with a cable closely calculated for the current it had to carry, the current density might possibly have to be diminished merely to obviate this additional drop, apart from any other consideration.

For a cable working at a high load factor the extra loss of energy due to the enhanced resistance from heating can scarcely be neglected. With ordinary types of underground mains the effect of heating on the regulation or the economy is of less importance than the physical results it may produce on the insulating covering. Most of the impregnating liquids for fibre or paper cables will begin to vaporise in air at 100°C., and probably this is accompanied by injurious chemical changes. At lower temperatures these changes would be smaller, but re-actions similar to those at the higher temperature would tend to be produced, although in a correspondingly less degree. Where vulcanised bitumen is used as the dielectric the temperature must be limited with special reference to the tendency of the conductor to decentralise when hot, and for this reason the permissible current densities for this class of cable are less than the usual values.

The great engineering desideratum with buried cables is that they should require a minimum of maintenance, and that

they should never be run under conditions that would cause any shortening of their reputed useful life of 30 or 40 years. The greatest current density that can be permitted in a buried cable depends chiefly on the maximum temperature which the insulation can safely stand. The rise of temperature, in its turn, is dependent on several factors, among which are the following :—

1. The character and amount of the load, whether of long or short duration and of constant or variable value.

2. The depth of trench in which the cable is laid and the character of the soil, whether wet or dry.

3. The size and construction of the cables.

4. The method of laying, whether in ducts or direct in the ground, singly or several cables bunched in the same trench
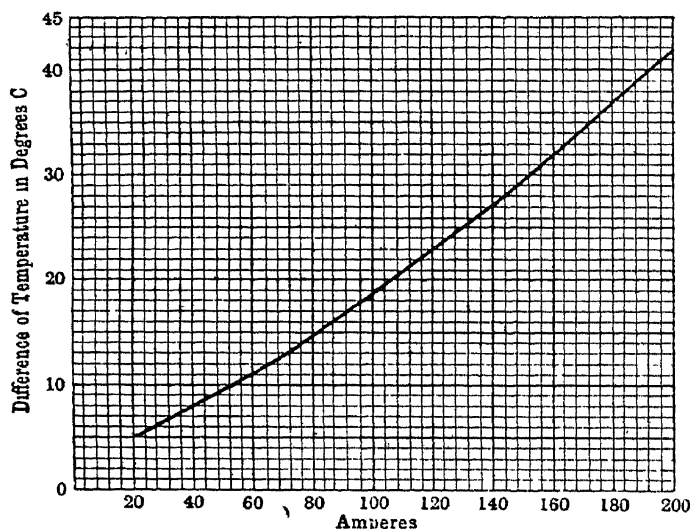
FIG. 31.

Amount of Temperature Rise.

In a cable carrying a steady current the final temperature is only attained after several hours, the exact period depending on the conductivity for heat of the soil, its specific heat and the temperature at the surface of the ground. The relation between the rise in temperature and the current, after a steady state has been reached, is indicated in Fig. 31.   When the

values of the temperature with respect to time are plotted in a curve its form resembles that of the successive readings at short intervals of a Wright demand indicator under a constant current, until they become asymptotic to the final value.

The physical reason is the same in both cases. In Fig. 32 the " time lag" is illustrated graphically (curve A) for a single armoured cable laid direct in the ground, and also the effect produced by bunching the cables. Curve B refers to a group of nine cables of the same cross-section as the single one, and each carrying the same constant current. The temperature in the latter case rises more quickly and ultimately attains a higher value. From these curves it is apparent how important it is to know how the cable is laid.
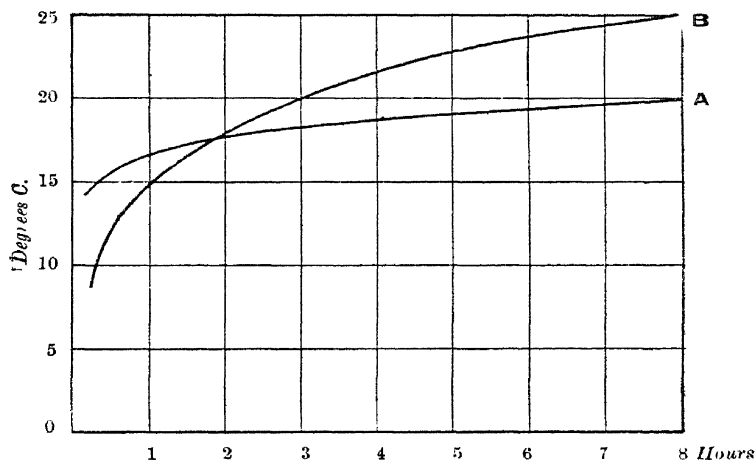
FIG. 32.

The character of the soil, except for the amount of moisture it contains, does not affect materially the curve of temperatures. In perfectly dry earth the final temperature of a cable is found to be about 10 per cent. higher than that of another tested under the same conditions but with 20 per cent. of moisture in the soil. As it is but rarely that cables are laid in ground devoid of moisture, the effect produced by its varying amount can be safely neglected. It is of interest to note that, for the same temperature rise, a cable laid under water will stand 50 per cent. more load than a cable buried in ordinary soil.

Law of Temperature Rise in Buried Cables.

The physical law for the flow of heat from a cable into the ground is analogous to that of the potential gradient in the insulation of a cable, and can be expressed by a similar logarithmic formula. When a single buried cable of unit length, carrying a current for some hours, has reached a steady temperature, t, this will be proportional to the quantity of heat, H, produced in it, and to the resistance to the flow of heat (R) into the surrounding soil. If this is a good conductor, it will necessitate the generation of a greater quantity of heat in the cable to raise it to a given steady temperature. These facts, expressed by $H = \dfrac{t}{R}$, correspond to Ohm's Law for electric currents, $C = \dfrac{V}{R}$.

Thus the quantity of heat H is equivalent to current C, temperature t to pressure V, and heat resistance R to electrical resistance R.

The quantity of heat produced per unit length by the current C flowing in a cable of cross-section, s, is $C^2 \times$ resistance

$$= \frac{C^2 L}{K s} \text{ (and when } L = 1) = \frac{C^2}{K s}.$$

The determination of the heat resistance is much more difficult. Experimental researches into the physical facts, and their representation by a simple and comprehensive formula,* have not yet led to a universally accepted conclusion.

The analytical investigation is simplified if we assume the heat resistivity of the insulation round the copper to be small compared with that of the surrounding soil.

If we take a sectional view of the cable at right angles to its axis, and consider a cylinder of soil of unit length at a distance x from the cable and of thickness dx (Fig. 33), the resistance to the passage of the quantity of heat H through this is directly proportional to the heat resistivity, σ of the soil, and to the surface of the cylinder, and inversely proportional to its thickness. The surface is $2\pi x$, the thickness dx, and the heat resistance is $\dfrac{\sigma}{2\pi x} \cdot dx$.

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* *See* Proc. I.E.E. (Melsom and Booth), June, 1914.

Each concentric cylinder is an isothermal surface, or, it has the same temperature at any point of its surface.

We will assume first that the cylinder which is tangential to the earth's surface at a radius l (the depth of the trench) is the zero isothermal.

Then the whole resistance from the surface of the cable of radius r to this zero surface is

$$\int_r^l \frac{\sigma}{2\pi} \cdot \frac{dl}{l} = \frac{\sigma}{2\pi} \log_e \frac{l}{r} = \frac{\sigma}{2\pi} \log_e \frac{2l}{d},$$

and the equation $H = \dfrac{t}{R}$ becomes $\left(\text{since } H = \dfrac{C^2}{Ks}\right)$

$$\frac{C^2}{Ks} = t \left| \frac{\sigma}{2\pi} \log_e \frac{2l}{d}.\right.$$
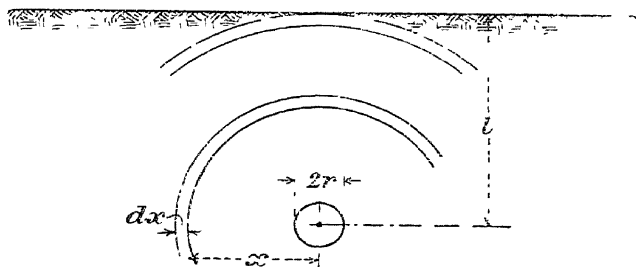
FIG. 33.

By zero isothermal is meant the surface from which the relative rise of temperature in the cable is measured, and it does not imply that the actual temperature is zero.

The work of Kennelly has shown that it is more correct to assume the plane of the earth's surface as the zero isothermal instead of the cylinder of radius l tangential to the earth's surface.

The construction of the formula corresponding to this assumption is too complex to reproduce here, but Kennelly found that if $\dfrac{l}{d}$ is large, as it is in practice, the heat conduction equation is :—

$$\frac{C^2}{Ks} = t \left| \frac{\tau}{2\pi} \cdot \log_e \frac{4l}{d}.\right.$$

The V.D.E. in the preparation of its standard table of current densities has accepted this interpretation. If we call the constants

$$\frac{\sigma}{2\pi}=A \text{ and } \frac{sK}{C^2}t=y$$

the equation becomes $y=A\log.\frac{4l}{d}$ (a straight line law connecting y and $\log.\frac{4l}{d}$).

The graphical representation of a number of experimental observations of y and $\log.\frac{4l}{d}$ is given in Fig. 34.
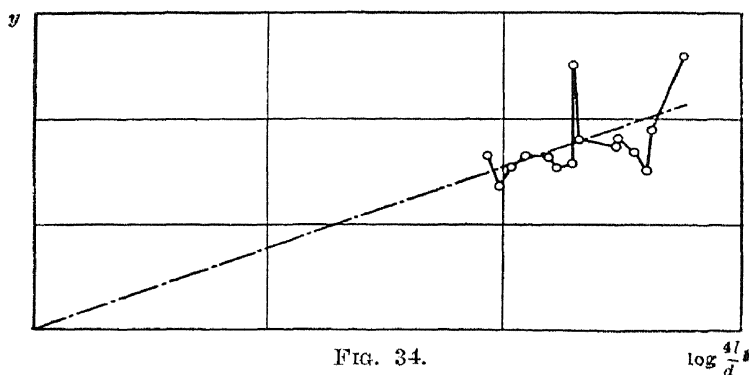
FIG. 34.

The straight line, averaging the values as plotted from the experiments, passes through the origin, thus indicating general agreement between the formula and the experimental facts.

For practical work the formula is conveniently written :—

$$\frac{C^2}{Ks}=t\left/\frac{\sigma}{2\pi}\right. \cdot \log_e\frac{4l}{d},$$

$$C^2=\frac{\sigma K}{2\pi}\cdot st/\log.\frac{4l}{d}$$

$$=M^2\cdot st/\log_e\frac{4l}{d}\left(\text{where } M^2 \text{ is a constant}=\frac{\sigma K}{2\pi}\right),$$

$$\text{or}\quad C=M\sqrt{\frac{st}{\log_e\frac{4l}{d}}}.$$

When *s* is in square inches, *t* in degrees C, *l* and *d* in inches, the value of M, from experiment, is 300 approximately.

If, for any reason, it should be desirable to work at a temperature different from that given in the usual tables, for instance, in tropical climates, the formula enables the permissible current C to be calculated. Similarly, for any variation in the cross-section *s* or changes in *l* and *d*, the proper values of C can be ascertained.

Modifying Effects. Methods of Laying. Bunching of Cables.

In using a table of current densities the facts it embodies should be carefully borne in mind. The formulæ and the observed facts agree fairly closely in the case of armoured cables laid direct. For other methods of laying there is not much information available, to enable the working current densities to be derived from the corresponding values with cables laid direct.

Mr C. Beaver has given some figures for the temperature rise under various conditions of a 0·5 sq in. cable, at a current density of 1,500 amps. per sq. in. After 10 hours' running the temperature rises were as follows :—

(1) Armoured cable laid direct . ... 48°F.

(2) Lead covered in asphalt trough .... 53°F.

(3) Lead covered laid solid .... 98°F.

(4) Lead covered drawn in .... 85°F.

The V.D E. rule recommends, with the systems of laying (2), (3) and (4), that the current density should be reduced to 75 per cent. of that in (1).

But it is apparent from the figures that this simple correction is insufficient, and further experimental work must be done to get the accurate relationships of the various systems.

Where several cables are laid in the same trench the symmetry of the isothermal cylinders is broken, and the heat produced in any one cable does not pass freely into the soil, owing to the influence of the other cables. Each cable in the

group, therefore, ultimately assumes a higher temperature than if it were laid singly. For a group of three or more laid together a safe rule is to diminish the current densities to 75 per cent. of those for single cables laid direct.

Modifying Effects.   Depth of Trench.   Variable Loads.

The heat capacity or specific heat of the earth has a considerable effect on the temperature rise when the load is not constant nor long continued, as it requires some time to heat the layers of soil until they become steady isothermal surfaces. This is clearly shown in Fig. 32   The period required for the attainment of an absolutely steady state is measured in days rather than hours, but practically six to ten hours are sufficient.

Thus a higher current density can be permitted when the load is only of short duration as in the case of certain feeders at times of peak   Some latitude can also be given with cables supplying rapidly fluctuating loads, such as lifts, cranes, rolling mills, &c.   The extent to which this is allowable can be ascertained by taking the square root of the mean of C^2 just as in the exact application of Kelvin's law.   The only other variable in the expression for permissible current is l, the depth at which the cable is laid.   In the tables this is taken as 28 in., which agrees with general practice, leaving special cases to be dealt with by the help of the formula.

Heating of Three-core, Concentric and H.T. Cables.

It was at one time believed that, with multicore cables, if the sum of the cross-sections of the cores were taken and treated as a single cable, the permissible current for the latter could be divided among the cores proportionately to their respective cross-sections, and thus determine their working currents.   Experience has shown, however, that this simple calculation is not justified except in the case of very small cables.   The correct values have to be obtained experimentally, and they prove to be higher than those based upon the equivalent single cable.

With concentric cables a fairly accurate working formula is given below :—

$$C_2 = C_1 / \sqrt{\lambda z}.$$

C_2 =permissible current in one conductor of the concentric cable.

C_1 =permissible current for single cable.

z =number of conductors (assumed to be of equal section) in the cable.

λ =multiplying factor being 0·92 for simple concentric and 0·77 for triple concentric of standard makes.

The diminution in the carrying capacity of concentric and multicore cables is due partly to the bunching of the conductors, and partly to their being surrounded by several layers of insulation, impeding the flow of heat from the conductors into the soil.

Concentric instead of single cables would appear to be disadvantageous for feeders on account of the higher temperature produced in them with the same current density For example, a 0·25 concentric will only carry 300 amperes, as compared with 390 amperes if the conductors were laid separately. Thus, the section of a concentric feeder, especially if laid in a stoneware duct, could seldom be calculated in accordance with Kelvin's law of Economy, for the current density satisfying the latter condition might cause too high a rise of temperature. Consequently, concentric cables, to take the same loads as single cable feeders, will be heavier, and, inclusive of laying, will probably prove more costly.

The effect of increased thickness of the layers of insulation is very marked in the case of E.H.T. cables. Lichtenstein's experiments showed that a cable of this class reached a temperature of 40°C., when carrying a current which would heat low tension cable of the same section only to 25°C. Owing to the very divergent thicknesses of insulation in E.H.T cables of different makes, it is impossible to give a general comparative rule based on the values for low tension cables, and special tables of current densities should be used.

For high tension cables it is a fairly safe procedure to limit their current densities to 75 per cent. of those for the same sizes of low tension cables.

With E.H.T. cables worked at pressures above 20,000 volts, the energy lost in the dielectric—due to dielectric hysteresis—may cause temperature rises which are far from negligible. At 30,000 volts the rise due to this cause alone may be about 10°C., and it must be added to that due to the C^2R losses.

Effects of Temperature on Insulation and on Cable Fittings.

It has frequently been stated that there is a great likelihood of the insulation breaking down under dielectric stress when the cable is running hot. Careful experiments have failed to verify this, although they have proved that the insulation resistance
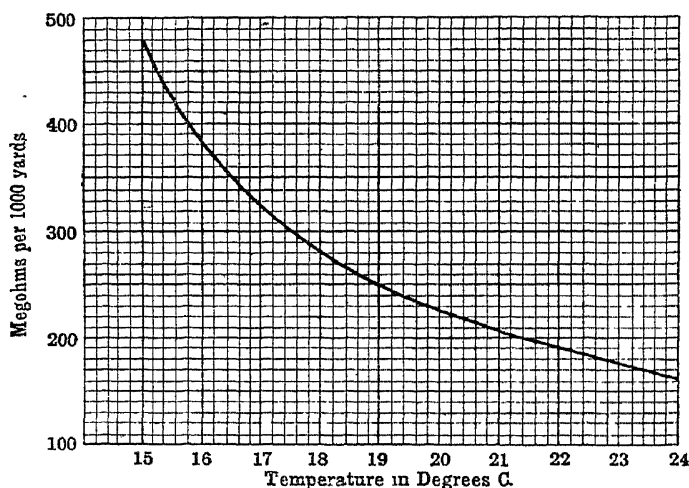
FIG. 35.

in megohms diminishes very considerably at high temperatures, a phenomenon shown graphically in Fig. 35. An increase of 20°C. will cause the insulation resistance of a paper cable to drop to 3 per cent. of its value at ordinary temperatures, but this has no observable effect on the dielectric strength (*see* Paper by E. Jona, St. Louis International Congress, 1904). The crucial factor in fixing the safe limit of current density would, therefore, appear to be the temperature below which the chemical stability of the dielectric remains unaffected.

. Mention may be made of another consequence of the heating of cables.

This is the possibility of the fittings in joint and disconnecting boxes being so strained by alternate expansion and contraction that the electrical connections are ultimately broken, or great difficulty may be found in replacing the links after they have been removed for testing.

With lead-covered cables, particularly when drawn into ducts so that there is plenty of freedom for movement, the plumbed joints are liable to be broken.

Mr. H. Gray, of Accrington, who has given considerable attention to this phenomenon, has devised and patented a special construction of cables for taking up the expansion at every point along their length. Cables of this kind are now being made by Messrs. Glover.

A sufficient amount of play is allowed between wire and wire on the same lay, and all motion due to contraction or expan-
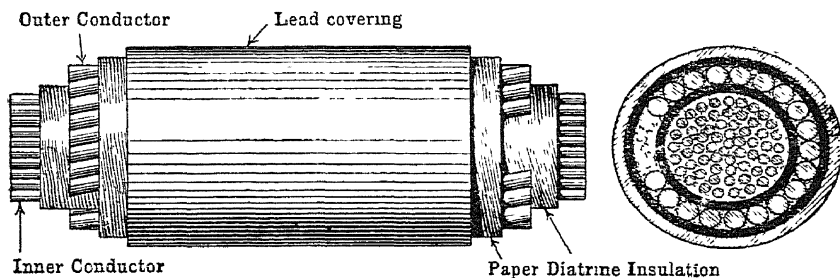
FIG. 36.—EXPANSION CABLE. TWO-CORE CONCENTRIC, 0·5 SQUARE INCH.
(Scale: Half full size)

sion is taken up locally, so that no bodily displacement of the ends can occur. The illustration of a concentric cable built to this specification (Fig. 36) will render the principle clear.

With a " solid " or " armoured direct " system the effects of temperature changes are less serious than with drawn-in cables, but with them trouble will also be experienced if they are laid too taut.

Comparative Tables of Permissible Current Densities.

The most frequently used table of maximum working currents is that embodied in the I.E.E. Wiring Rules, but it should not be forgotten in referring to it that the figures are not primarily applicable to buried cables nor to any make except those with single conductor.

For heavy paper or fibre-insulated cables the temperature rise has been reckoned as 50°F. or 28°C. The I.E.E rules give rather low values for buried cables, which can actually withstand heavier loads than the same cross-sections used in installation work.

The V.D.E. as already mentioned, have made extensive, investigations, theoretical and practical, before deciding on the values in their tables.

They are based upon a temperature rise of 25°C. and a 700 mm. (28 in.) standard depth of trench.

The normal temperature of the soil is assumed to be 25°C., so that the cables themselves may ultimately reach a temperature of 50°C.

For facility of comparison, the lists of safe currents for the standard British sections, as published by the British Insulated & Helsby Cables Co. and by Callender's Cable Company, are

Safe Currents recommended by the British Insulated & Helsby Cables Co. for Paper-insulated and Lead-covered Cables, drawn into Stoneware Conduits. Initial Temperature, 60°F., and allowing for a safe rise of 90°F. under Continuous Load

Size cable. Sq in.	Amperes when				
	Single.	Concentric.	Twin.	Triple.	Three core.
0 0125	50	39	43	30	37
0·025	85	67	74	51	64
0 05	141	111	123	84	106
0·075	182	143	158	109	136
0·1	220	174	191	132	165
0·125	250	197	218	150	187
0·15	280	221	244	168	210
0 2	337	266	293	202	252
0·25	388	306	338	233	290
0·3	435	344	379	261	326
0·35	480	379	417	288	360
0 4	525	415	456	315	394
0·5	600	474	522	360	450
0 6	684	540	508	410	512
0 7	750	592	653	450	562
0 8	815	643	710	490	610
0·9	880	695	765	528	660
1·0	930	735	810	558	693
1·25	1,080	850	940	648	810
1·50	1,210	955	1,050	725	906

Safe Currents for Single Cables laid Direct in the Ground at a Depth of 28 in. Temperature rise, 25°C. (Verband Deutscher Elektrotechniker.)

Cross-section in square inches.	Current in amperes.	Cross-section in square inches.	Current in amperes.
0·016	95	0·23	510
0 025	130	0·29	575
0 04	170	0·37	670
0 054	210	0·48	785
0 077	260	0·62	910
0·11	320	0·77	1,035
0·15	385	1·0	1,190
0·19	450	...	.

Table of Maximum Current Densities as recommended by Messrs. Callender. Temperature rise not stated.

Cross-section in square inches.	Maximum current in amperes.	Cross-section in square inches	Maximum current in amperes
0 1	100	0 5	430
0 15	145	0 6	500
0 2	190	0 7	560
0 25	240	0 8	615
0 3	285	0 9	660
0 35	330	1 00	700
4 0	370	...	..

also given. The B.I.&H. Company's figures relate to paper-insulated lead-covered cables drawn into stoneware ducts, and correspond to a rise of 90°F. To render them comparable with the values given by the V.D E., the latter must be multiplied by 0·75, the allowance advisable for drawn-in cables. The limits fixed by Messrs. Callender for the safety of their cables in running are much lower than those given in either of the other tables.

For a historical summary of the work done in investigating this subject, up to a recent date, the Paper by Messrs. Melsom & Booth, " Proc." I.E.E., June, 1914, should be consulted.

CHAPTER VII.

———◆———

NETWORK ANALYSIS.

Kirchhoff's Laws.   Superposition of Currents.

The usual objects in view in the analytical treatment of a network, or more frequently a small portion of it, are, firstly, to ascertain if any conductor is being overloaded, and, secondly, to find out the exact voltages at those points which possess no pilot wires, and which might be thought from their position, and the loads in their neighbourhood, to require special investigation. Continental writers on the design of mains systems seem to regard it as essential to use analytical methods to verify the sizes of all conductors, which have been obtained by the simplified process of assuming the positions of the cutting points as exactly midway between feeders. In England, apparently, such accurate analysis is seldom attempted, but occasions may arise when it will yield useful results.

The principles employed are ultimately dependent on Kirchhoff's laws, although in their standard form these alone are not very convenient to use. They are, however, repeated here for easy reference :—

1. The algebraic sum of all the currents meeting at a point is nil.

2. In any closed circuit the sum of all the E.M.F.s is equal to the sum of the products of each current into the resistances which it traverses, or

$$\Sigma(e) = \Sigma(c \cdot r).$$

The law of the superposition of currents, which is of equal importance in dealing with networks, may be stated as follows :

The current which passes through a definite section of a conducting system (if various currents are led into and out of the section at different places) is equal to the algebraic sum of the currents flowing through that section if these are considered, not as acting simultaneously, but one after the other. To illustrate this law with the triangular system of conductors A, D, B (*see* Fig. 34), in which the currents C_1 and C_2 enter at A and D respectively and the total current $C_1 + C_2$ leaves at B, if the currents in the branches r_1, r_2, r_3 are worked out by

considering C_1 alone, and afterwards C_2 alone, the super-position of the two results will give the true values in each branch.

If C_1(Fig. 37)is 4 amperes,and the resistances are $r_1=5$ ohms, $r_2=7$ ohms, $r_3=6$ ohms, it will divide up through these, so that the current in A to B is 2·66 amperes, in A to D 1·33 amperes, and in D to B 1·33 amperes. Similarly, the current C_2 of 9 amperes, if considered separately, will divide up in passing to B, so as to give 3·5 amperes from D to A (or —3·5 from A
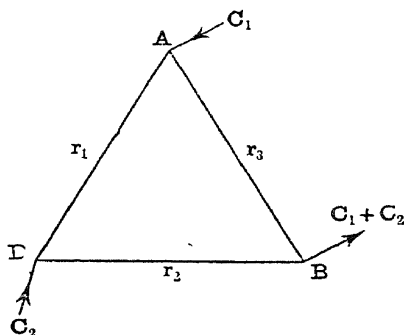
FIG. 37.

to D), 3·5 amperes from A to B, and 5·5 amperes from D to B. By superposing these values we find the total current in each branch :—

AB$=2·66+3·5=6·16$ amperes.
AD$=1·33—3·5=—2·16$ amperes (or $+2·16$ from D to A).
DB$=1·33+5·5=6·83$ amperes

These values can be checked by applying Kirchhoff's first law to the points A, D and B.

At A the Σ $(c)=$ $4+2·1\dot{6}—6·1\dot{6}=0$.
At D the Σ $(c)=$ $9—2·1\dot{6}—6·8\dot{3}=0$.
At B the Σ $(c)=13—6·1\dot{6}—6·8\dot{3}=0$.

" Cutting Point " or Current Method for Networks.

One of the most frequently used analytical methods with meshed conductors is that known as the " cutting point " or current method. This consists in arbitrarily selecting any point in the closed mesh, from and into which currents are led, and assuming that the conductor is cut at that point. If, now, the currents flowing to and from this point are separately·

considered, an equation is obtained from Kirchhoff's law expressing the equality in the P.D.s between the cutting point and the point of supply, going round the mesh by two different routes.

Taking the simple case of a closed circuit with one feeding point at A (*see* Fig. 38), the branches represented by C_1 to C_5 will be supplied as shown by the arrows, until one of them, for instance, C_3, at the cutting point, draws current partly from each direction. If the proportionate amount going by AB is called x, the balance (C_3-x) must come via AF.

Remembering now that the P.D.s from A to C_3 by both routes must be equal, the following equation obtains :

$$C_1 r_1 + C_2(r_1 + r_2) + x(r_1 + r_2 + r_3) = C_5 r_6 + C_4(r_5 + r_6) \\ + (C_3 - x)(r_4 + r_5 + r_6)$$

From this equation x can be found, and its sign $+$ or $-$ will
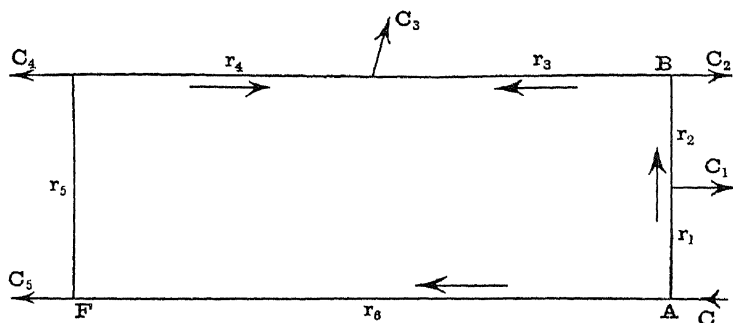
FIG. 38.

indicate if the assumed point of partition is the correct one The process will be clearer from the following example, in which the cutting point is selected arbitrarily, but so that it is obviously incorrect—say at B, Fig. 39.

The values, in amperes, of the currents are set against the arrow heads and the resistances, or lengths of uniform cross-section of conductor, are marked between the points of branching. Then

$$(2 \times 3) + (x \times 4) = (5 \times 7) + (7 \times 10) + (6 \times 12) + \{(4-x) \times 16\},$$

from which $x = 11.75$.

It is at once apparent that B is incorrectly chosen, since the total current drawn from B is only 4, leaving 7·75 to go on to L.

The point L must next be considered, and it will be seen that it takes 6 off the total of 7·75, leaving 1·75 to go on to D, which is the correct point sought. D therefore takes 1·75 via AL and 5·25 via AFD. Assume the point of partition next at P, then

$$(2 \times 3) + (4 \times 4) + (6 \times 8) + (7 \times 10) + (x \times 13) = \{(5 - x) \times 7\},$$

from which $x = -5\cdot25$, confirming the former result.
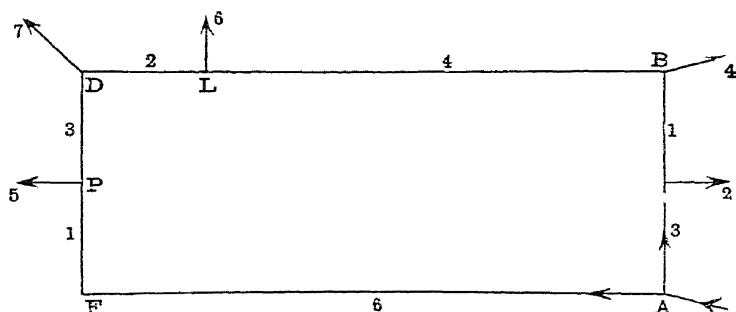
FIG. 39.

The negative sign indicates that the flow of current in the section DP is in a contrary direction to that assumed, and is in reality from P to D. As 5·25 is only a part of the total current at D, it is at once apparent that the true cutting point is situated there.
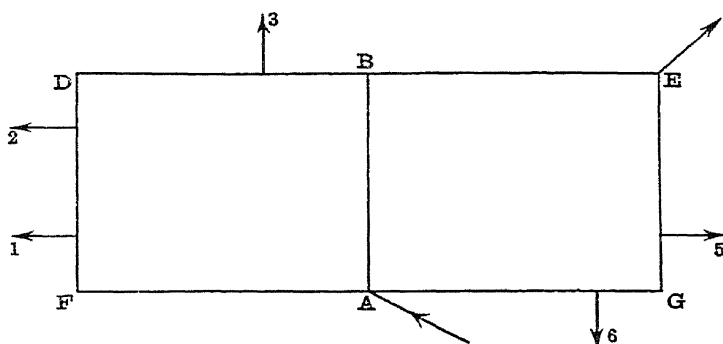
FIG. 40.

This example shows clearly that the general equation furnishes the correct position, wherever it may originally have been assumed.

Proceeding to a set of conductors forming two meshes, ABDF and ABEG (the whole being fed at A, Fig. 40), the

problem is somewhat more difficult, since a neutral point has to be found on each mesh.

By making similar assumptions to those just described, two simultaneous equations are obtained, x indicating the current flowing from A to F and y that from A to G. The solution of these equations gives the complete determination of the currents in every part of the system.

With three meshes there would be three unknown quantities, x, y and z, to be determined, and for a network of n meshes there would be n simultaneous equations to solve. This is a long and laborious process, which is practically possible only with the help of determinants
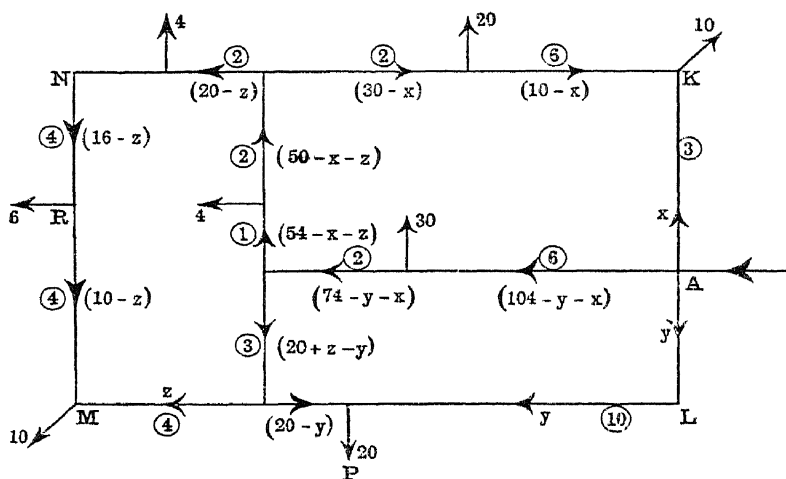
FIG. 41

The essential rule in choosing the cutting points before writing down the simultaneous equations is to arrange that each mesh is opened so that there is only one path by which each load current is supplied from the feeding point. The three-meshed network LMNK, which is fed at the point A, will illustrate clearly the algebraic methods. The positions and magnitudes of the consumers' loads in amperes are as shown, and for simplicity the cables are taken to be of one cross-section throughout. Should this vary a correction must be applied by dividing each length by its cross-section, so as

to make the lengths exactly proportional to their several resistances, and enable the former to be used instead. The figures in circles in Fig. 41 are the lengths of main between each consumer or point of branching.

The first step is to assume the meshes cut at three points, so that no consumer is fed from two directions, except those at the cutting points. The network is then everywhere resolved into open branches. instead of closed loops. Let the cutting points be taken at K, P and M, and let the unknown currents reaching them by the shortest route from A, the feeding point, be x, y and z respectively. The currents in all the other sections can then be written down, as shown in the figure, in terms of x, y and z, by working backwards from the cutting points. From Kirchhoff's second law, and the current values, the three equations connecting x, y and z are derived, each expressing the equality of the drops to the cutting point, going round the mesh in two directions from its point of supply.

(1) $x \times 3 = (104 - y - x)6 + (74 - y - x)2 + (54 - z - x)$
$$+ (50 - z - x)2 + (30 - x)2 + (10 - x)6.$$

(2) $y \times 10 = (104 - y - x)6 + (74 - y - x)2 + (20 - y + z)3$
$$+ (20 - y)1.$$

(3) $z \times 4 + (20 - y + z)3 = (54 - z - x)1 + (50 - z - x)2$
$$+ (20 - z)2 + (16 - z)4 + (10 - z)4.$$

After simplification,

$$
\begin{aligned}
(1) \qquad & 1{,}046 = 22x + 8y + 3z, \\
(2) \qquad & \phantom{1{,}0}852 = 8x + 22y - 3z, \\
(3) \qquad & \phantom{1{,}0}238 = 3x - 3y + 20z.
\end{aligned}
$$

From (1) and (2) $\qquad 1{,}898 = 30x + 30y,$

 (2) and (3) $\qquad 17{,}754 = 169x + 431y,$

$$y = 26 \cdot 8 \ ;$$

and by substitution $\qquad x = 36 \cdot 5,$

$$z = 10 \cdot 4.$$

The currents in each length, originally stated in terms of x, y and z, can now be written down and are represented in

Fig. 42   From these and the cross-sections the voltage drops
at any point can be calculated   The greatest drop is at the
point R.   It will be observed from the current values and
directions that there are no true cutting points in the meshes
nearest the feeding point, although these were tentatively
assumed to commence with.   R is the only actual cutting
point.

It is important, also, to notice the sign of the numerical
values of the current flowing in each section.   Should it be
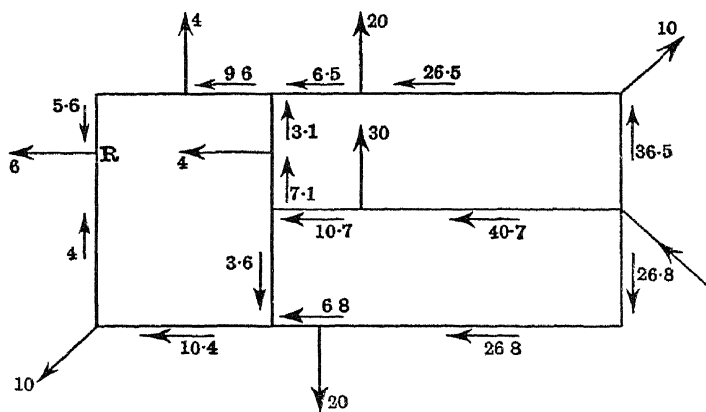
FIG. 42.

+ it shows that the direction first assumed is the correct one,
but if it turns out to be −, the direction first supposed must
be reversed.

In the present example the actual drop to the point R is
3·2 volts, if the unit of length is taken as 10 yds. (*i.e.*, length
10=100 yds.) and the cross-section of main as 0·05 sq. m.

Voltage Method of Network Analysis.

Instead of considering the currents as the independent
variables, it is, in many cases, preferable to study the
distribution of the voltages in the network.   If this is
fairly supplied with pilot wires to the feeding points the
investigator is at once furnished with a number of constants
in his equations, and small portions of the network can be
conveniently dealt with separately.   It is not much, if any,

simpler than the " cutting point " method just exemplified, but the reuslts obtained are more directly useful. After all it is the points of lowest voltage the mains engineer wishes to determine, so that bad conditions can, if possible, be improved. As will be seen, the algebraic routine is much the same as in the former case, and involves the solution of n simultaneous equations, if there are n meshes in the network. For the sake of comparing the two methods the same small network will be considered, with the same dimensions and loading as before. (Figs. 41 and 42.)

On looking at this it will be seen to possess four points where the conductors intersect—usually called the nodes. The voltage v at one of these nodes is known, as it is a feeding
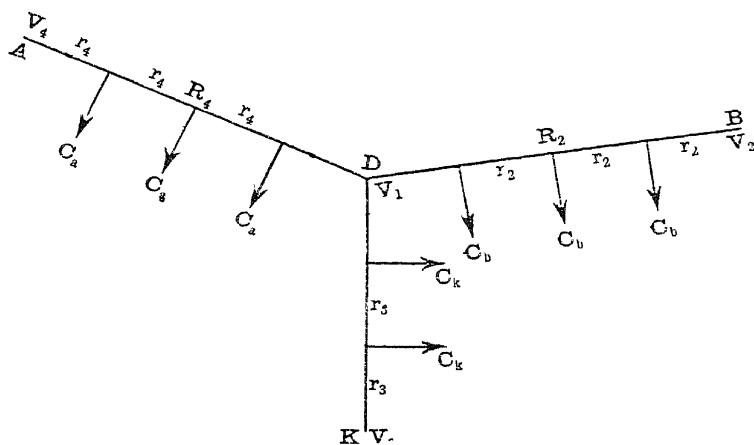
Fig. 43.

point, and three equations can be written down expressing the relation between this voltage v and the unknowns, c_1, v_2 and v_3. From our previous investigation of the composition and resolution of currents, the equation

$$C_2 = \frac{V_2 - V_1}{R} + \frac{\Sigma_1^{n}(c.r)}{R}$$

holds good for any conductor, where V_1 and V_2 are the end voltages, R is the total resistance, and $\Sigma(c.r.)$ is the sum of the moments of the currents reckoned from the point V_1 and C_2 is the current entering the node at C_2.

In Fig. 43, if the load currents in AD are generically C_a, the

resistances from A are r_4, and the total resistance R_4, then the sum of the moments of the load currents about A is $\Sigma C_a r_4$. The resultant current at D is equal to

$$\frac{V_1 - V_4}{R_4} + \frac{\Sigma C_a r_4}{R_4}.$$

Similarly, for DB the resultant current is

$$\frac{V_1 - V_2}{R_2} + \frac{\Sigma C_n r_2}{R_2},$$

and for DK is

$$\frac{V_1 - V_3}{R_3} + \frac{\Sigma C_n r_3}{R_3}.$$
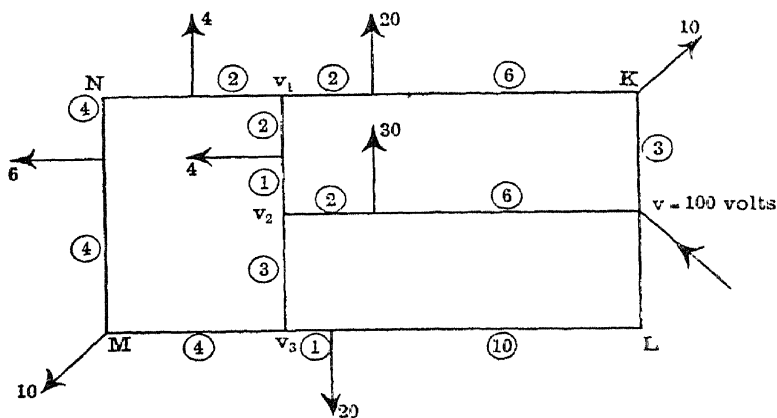
FIG. 44.

By Kirchhoff's first law the sum of these three currents is zero, thus leading to the following equation :

$$\frac{V_4 - V_1}{R_4} + \frac{V_2 - V_1}{R_2} + \frac{V_3 - V_1}{R_3} = \frac{\Sigma C_n r_1}{R_4} + \frac{\Sigma C_n r_2}{R_2} + \frac{\Sigma C_n r_3}{R_1}.$$

If there are n conductors meeting at the node D, there will be n terms on each side of the equation. It is obviously necessary to have a sufficient number of similar equations of this form (in the present example three) before the unknown quantities can be found. The statement of these equations with a closed network is always possible, but if it consists of complicated meshes intervening between the feeding points,

where the voltage is known, the set of simultaneous equations may amount to a considerable number. In such circumstances recourse must be had to determinants for facilitating the solution. Numerical examples embodying their use are out of place in this work, but the instance now considered shows clearly the application of the general theory.

Referring to the plan of the network and its loading, as shown in Fig. 44, the following relations between the voltages at the four nodes v_1, v_2, v_3 and v, which is the supply pressure of 100 volts, can be at once established :—

(1)
$$\frac{v - v_1}{g(2 + 6 + 3)} + \frac{v_2 - v_1}{g(2 + 1)} + \frac{v - v_1}{g(2 + 4 + 4 + 4)}$$

$$= \frac{20 \times 9 + 10 \times 3}{11} + \frac{4 \times 1}{3} + \frac{4 \times 12 + 6 \times 8 + 10 \times 4}{14}$$

(2)
$$\frac{v - v_2}{g(2 + 6)} + \frac{v_1 - v_2}{g \cdot 3} + \frac{v_3 - v_2}{g \cdot 3} = \frac{30 \times 6}{8} + \frac{4 \times 2}{3} + 0.$$

(3)
$$\frac{v - v_3}{g(1 + 10)} + \frac{v_1 - v_3}{g(2 + 4 + 4 + 4)} + \frac{v_2 - v_3}{g \cdot 3}$$

$$= \frac{20 \times 10}{11} + \frac{10 \times 10 + 6 \times 6 + 4 \times 2}{14} + 0.$$

The quantity g is the resistance in ohms per unit length of the conductor; in this case it is ·01 ohm. per ten yards, forward and return, of 05 sq. in. cross-section. On the right-hand side of the equations g cancels out, as it appears in each r and R.

The solution of these equations gives the following results :—

$$v_1 = 97 \cdot 2,$$
$$v_2 = 97 \cdot 34,$$
$$v_3 = 97 \cdot 24.$$

These can be checked by working out the several drops to the same points from the values of the current in the conductors already found by the " cutting point " method.

From these values of v, v_1, v_2 and v_3, and the known resistances and loads, the current in every section of the system can be ascertained, in order to see that the safe current density is nowhere exceeded.

CHAPTER VIII.

POWER NETWORKS.

General Conditions for Power Mains.

A distribution system supplying a power load only is not subject to the same narrow limits of working pressure or voltage regulation as a lighting network, and the amount of copper to deal with the same output can be made substantially less. In the lighting distributors the drop in pressure must not exceed the legal limit. Three or four times this amount can be allowed in mains for power only, as the effect of low voltage on motors is not so serious as on incandescent lamps.

The voltage drop in the mains does not unduly affect the efficiency of direct current motors, although it reduces the working speed, but this can be allowed for, in relation to the machinery operated by adjusting the ratios of the driving gears. With alternating or polyphase motors the speed is independent of the pressure drop in the distributing system as long as the frequency is kept constant. The question of speed regulation is of great importance in many industries, such as the textile, and in no application of electric driving is it negligible. Even where a consumer pays only for true watts, measured through a wattmeter, he should insist on having the voltage and frequency kept within reasonable limits. The consequence of running at low speeds due to voltage or frequency variations is that the output per machine-hour is correspondingly less, and the consequent annual loss for a whole factory or works may amount to a considerable sum.

Polyphase motors exhibit a decided advantage over direct current in respect to constancy of speed.

It will be seen, then, that the conditions for power and lighting networks are very different, and the common practice of making a network to serve both purposes renders the capital cost *qua* power a good deal higher than it might be. In the majority of installations, up till now, the same mains

furnish both power and light, but for industrial areas, where it is hoped ultimately to satisfy practically every demand for power by electrical means, it is at least worth considering whether it would not pay to put down a separate network for power.

There is every probability that the price of electric energy could be made substantially smaller than with a common network. Incidentally, some saving could be effected in the consumer's installation owing to there being no necessity for expensive motor starters, which are indispensable on lighting mains so as to prevent fluctuations in the pressure.

Design of Power Networks.

The design of a power network is usually dependent on the condition that the energy lost in the mains should not exceed a certain proportion of that usefully employed up to a limit of, say, 10 per cent., and the maintenance of a constant pressure within small percentage limits is a secondary matter The question, then, to be settled is how best to choose the sizes of all the conductors in relation to the percentage loss allowed

The voltage for the purpose of this investigation can be taken as fixed, and if it be decided to have a low-tension system it would not exceed 500 The actual value of the voltage does not affect the problem, and for extensive areas, with heavy loads, it may give the highest absolute economy to use a pressure of many thousand volts with secondary networks at lower pressures.

The issue having been narrowed by the careful choice of a working pressure, and the percentage loss of power allowable, the condition characterising the best sizes of the conductors is that the total weight or volume of copper in them is a minimum. To avoid complications the system of conductors is assumed to be like a set of feeders supplying a tramway, so that there are usually no closed loops or equalising mains.

The power lost in the mains is p, equivalent to x per cent. of P_s, the total power transmitted from the station

$$p = \Sigma \frac{lc^2}{Ks} \cdot f \qquad \text{(the resistance being } \frac{l}{Ks} \text{ as before),}$$

where c is the effective current in any conductor of the system of length l and cross-section s. The constant factor f is

dependent on the choice of the system, being 2 for a two-wire direct or alternating and 3 for a three-phase system

$$\text{Volume of copper} = W = \Sigma f \cdot l \cdot s.$$

In order that this quantity may be a minimum it has to be differentiated with respect to s and equated to zero. Then

$$\Sigma l \cdot ds = 0. \qquad \dots \dots \dots \quad (1)$$

If the expression for the power lost be also differentiated with respect to s and equated to zero

$$\Sigma \frac{l \cdot^2}{s^2} \cdot ds = 0. \qquad \dots \dots \dots \quad (2)$$

(c is not, strictly speaking, a constant, although treated as such in the above differentiation. No sensible error is introduced thereby, as a change in s, while keeping the loss the same, does not alter c much.)

If the equations (1) and (2) are simultaneously true, the coefficients of ds must be equal, or

$$\frac{c^2}{s^2} = \text{constant} = D^2 \text{ or } \frac{c}{s} = D.$$

This indicates that the current density, to satisfy the condition of minimum volume of copper in a system of mains having a definite percentage loss, must be constant throughout, or, conversely, if a constant current density is used, the amount of copper will be a minimum.

Law of Constant Current Density.

It will be observed that Kelvin's law is a particular case of the general law of " constant-current density." The percentage loss in the feeders under Kelvin's law is not fixed beforehand, but is dependent on the economic factors of the generating plant and mains taken together. Whatever its amount, it can be allowed for by regulating the pressure at the generating station so as to furnish what is necessary at the points where the power is used.

The fundamental difference between the design of lighting distributors for a minimum weight of copper, where the *voltage drop* is fixed, and that of power mains, where the amount of watts wasted is fixed, can be recognised by referring to the characteristic equation of the former problem, already considered at some length, which is $c/s^2 = $ constant.

Inserting the constant value of the current density $c/s = \mathrm{D}$ in the expression for the total watts wasted,

$$p = \Sigma f \frac{c^2 l}{\mathrm{K} s},$$

$$p = f \cdot \frac{\mathrm{D}}{\mathrm{K}} \Sigma cl.$$

In order to render this formula convenient for practical use, it is better to insert the known values of the horse-power taken by the motors instead of the current values. This substitution involves the value of the voltages. If the motors are at different distances from the station their voltages may vary considerably, but an average value V_a can be assumed, so that the power absorbed by the motors is

$$\mathrm{P} = n \cdot c\mathrm{V}_a \cdot \cos \varphi.$$

This is applicable to any system of distribution. With direct current $n=1$, $\cos \varphi = 1$; with three-phase $n = \sqrt{3}$, and $\cos \varphi$ is the power factor of the particular load. The expression for p, by substitution, becomes

$$p = f \cdot \frac{\mathrm{D}}{\mathrm{K}} \cdot \Sigma cl,$$

$$p = f \frac{\mathrm{D}}{\mathrm{K} \cdot n \mathrm{V}_a \cos \varphi} \cdot \Sigma \mathrm{P} l.$$

Dividing both sides by the total power taken by the motors $\Sigma \mathrm{P}$, this equation becomes, by the substitution on the left-hand side of

$$\frac{p}{\Sigma \mathrm{P}} = \frac{p}{\mathrm{P}_s} \cdot \frac{\mathrm{V}}{\mathrm{V}_a} = \frac{x}{100} \cdot \frac{\mathrm{V}}{\mathrm{V}_a},$$

and thus

$$\frac{x}{100} \cdot \mathrm{V} = \frac{f \cdot \mathrm{D}}{\mathrm{K} \cdot n \cdot \cos \varphi} \cdot \frac{\Sigma \mathrm{P} l}{\Sigma \mathrm{P}},$$

where x is the percentage loss allowed and V is the 'bus-bar pressure.

The expression $\dfrac{\Sigma \mathrm{P} l}{\Sigma \mathrm{P}}$ represents a length equivalent to a mean distance from the central point of supply which would

give the same losses if all the motors were installed there instead of in their actual positions. In this imaginary conductor of length l_m the volume of copper and the amount of power transmitted per square inch would be the same as in the actual mains. This conception of a mean length of main greatly facilitates calculations with the formula. Instead of expressing P in kilowatts, the horse-power rating may be used. The simplified formula becomes

$$\frac{x}{100} \cdot V = \frac{f \cdot D}{K \cdot n \cdot \cos \varphi} \cdot l_m.$$

This enables D, the current density, to be ascertained if $x/100$, the percentage loss in the mains, has been fixed upon. If no limit is laid down as to transmission loss, the best solution of the problem is obviously that given by Kelvin's law, which determines the current density and lets the total loss attain its corresponding value.

The formula, however, furnishes a ready means of indicating the total percentage loss with Kelvin's law. The rigorous application of the principle of a constant-current density involves a change of cross-section at every point where an installation is connected to a long length of main L. But it is possible to find an average current in the main, if a constant cross-section be taken (as is customary in practice), which will give the same loss of power. If $c_1 \ldots \ldots c_n$ are the currents in the various lengths $l_1 \ldots \ldots l_n$, the power lost is equal to $\Sigma(c_1^2 l_1 + c_2^2 l_2 + \ldots \ldots c_n^2 l_n = \Sigma_1^n c^2 l = C^2 L$ by hypothesis, where C is a constant current through the main. Then

$$C = \sqrt{\Sigma_1^n c^2 l} / \sqrt{L,}$$

and as $\dfrac{C}{s} = D =$ constant, s can be at once determined.

As an example of dimensioning conductors for power supply, let us take the installation set out diagrammatically in Fig 45, the outputs given in horse-power, and the distances from the sub-station S in yards.

We first find $lm = \dfrac{\Sigma Pl}{\Sigma P}$,

$$\Sigma P = 70 + 150 + 60 + 100 = 380,$$
$$\Sigma Pl = 70 \times 500 + 150 \times 400 + 60 \times 300 + 100 \times 600 = 173,000,$$

and

$$lm = \frac{173,000}{380} = 455 \text{ yds.}$$

The percentage loss is fixed at 6 per cent , and if the supply is across the outers of a 2×250 three-wire direct-current system V=500.

For this case f in the general formula is 2, n is 1 and cos φ also 1. The current density D is given by solving

$$\frac{x}{100} V . = \frac{f . D . l_{,,}}{K . n . \cos \varphi},$$

$$\frac{6}{100} . 500 = D \frac{2 \times 455}{40,000},$$

from which D=1,320 amperes per square inch.

To dimension the mains we must know the current taken by each motor. P is in *horse-power*, and the working efficiency is assumed to be 90 per cent

Then the current for any motor is

$$C = \frac{P \times 746}{V \times 0.9} = 1.66P.$$

The 70 H.P. motor requires 116 amperes, and the cross-section of its main $= S = \frac{C}{D} = \frac{116}{1,320} = 0.088$ sq in., or 0·1, nearest standard.
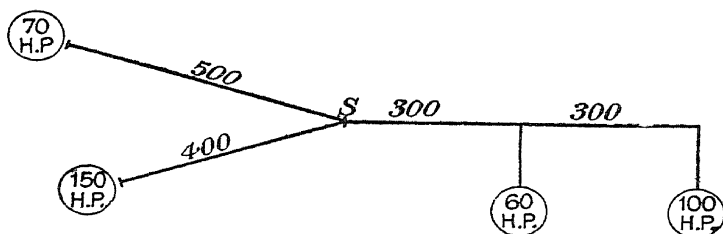
FIG. 45.

For the 150 H.P , $C = 150 \times 1.66 = 249$ amperes, $S = \frac{249}{1,320} = 0.19$, or 0·2 standard size.

For the 60 H.P., $C = 60 \times 1.66 = 100$ amperes, and for the 100 H.P. $= 166$ amperes.

To arrive at a uniform dimension for this main with two branches, we find the equivalent current

$$= \sqrt{\Sigma_1^{\;n} c^2 l} / \sqrt{L.}$$

$$= \sqrt{266^2 \times 300 + 166^2 \times 300} / \sqrt{600} = 218 \text{ amperes.}$$

$$= \frac{218}{1,320} = 0.165, \text{ or } 0.16, \text{ nearest standard.}$$

H 2

If the same installation is in a three-phase system with the same pressure of 500 volts between the conductors and with a power factor $\cos \varphi$ $=0·8$, the current density can be derived from that for the direct-current system by taking the ratios of $\dfrac{f}{n \cos \varphi}$ for both.

With direct current

$$\frac{f}{n \cos \varphi} = \frac{2}{1 \times 1} = 2.$$

With three-phase

$$\frac{f}{n \cos \varphi} = \frac{3}{\sqrt{3} \times 0·8} = 2·165.$$

Thus the current density for three-phase is

$$\frac{2}{2·165} \times 1{,}320 = 1{,}220 \text{ amperes per square inch.}$$

The currents corresponding to the outputs of the motors are found from the expression for horse-power P,

$$746 \times P = \sqrt{3} . C . V \cos \varphi \times \text{efficiency } (0·9).$$

Hence, $$C = P . \frac{746}{\sqrt{3} \times 500 \times 0·8 \times 0·9} = 1·2P.$$

For the 70 H.P., $C = 70 \times 1·2 = 84$ amperes, and the cross-section

$$S = \frac{C}{D} = \frac{84}{1{,}220} = 0·069 \text{ sq. in. (say, } 0·075)$$

Similarly the cross-sections of the other lengths can be calculated

This principle of constant-current density can be proved to be applicable also to any closed network supplied by a number of feeders, for such a system can be transformed into an equivalent one, in which the distributors are cut at the points of lowest potential between adjacent feeders, thus forming a set of " open " conductors, such as has just been considered. Thus the condition of constant-current density holds true generally for any system of power mains designed for a minimum volume of copper.

One awkward feature, as a result of this method of calculating cross-sections, manifests itself where there are one or two of the groups of motors fixed at distances from the supply point which are much longer than the average. In such cases the actual voltage at their terminals may exhibit such a large drop as seriously to affect their working speed. The cross-sections of their particular mains should then be adjusted so as to be heavier than that required by the formula. Natur-

ally the designer will have to be content with a less economy of copper than the maximum, but for such conditions this is unavoidable. The question of temperature rise must be considered in any of the current densities derived from the formulæ.

Where power is used in large units over an extensive area, as in shipyards, mines, &c., it would appear to be preferable (especially with overhead mains) to keep the conductors for power and lighting distinct. For town supply systems there are other circumstances that affect the question—for instance, the inconvenience of having two sets of mains and services, and the loss of the advantage due to the diversity factor of the lighting and power loads when supplied off the same conductors.

It is, however, important to keep clearly in view these fundamental differences in the principles of design of mains for the two classes of supply.

The possibility is hopefully contemplated by many engineers that electricity will, at no distant date, be used for heating and cooking at least as extensively as gas is now. In many places it is probable that the present modest sizes of mains in residential districts will prove insufficient to supply a demand of this kind, and, in these circumstances, a new network for power alone might be preferable. This could be worked at the maximum current density, irrespective of drop, and would, therefore, exhibit a substantial saving in capital cost. It would also assist the methods of charging, as contract rates with limiters or other devices could be made simply and safely for all electricity taken from the power network.

In view of the probable necessity for amplifying the system of mains for heating and cooking, it is important to keep the price at such a figure as will render any additional capital outlay remunerative. If this condition cannot be fulfilled, the proportion of electricity sold for heating and cooking, whenever it exceeds a certain amount, may cause a loss instead of a profit.

CHAPTER IX.

THREE-WIRE NETWORKS.

General Characteristics.

The general principles of design hitherto dealt with have been confined to the simple two-wire direct-current network. We must now consider what changes in the formulæ and methods are necessitated in their application to other systems, beginning with the three-wire system.

This was introduced into England by Dr. John Hopkinson and into America by Mr. Edison in the days when supply pressures over 115 volts did not exist, and when this limit was found seriously embarrassing. The three-wire arrangement is practically equivalent to working at twice the declared pressure on consumers' lamps, in so far as the feeders are concerned. In the distributing mains, if the loads between each outer and the middle wire are respectively equal and equally distributed, each positive load may be considered as running in series with the negative load at the same branching point, and the whole supply is at double the declared pressure. As these conditions of symmetry for every small part of the system do not hold in practice, a middle or neutral wire of reasonable cross-section is required for balancing. This conductor represents an extra amount of copper over that of a simple two-wire system at double the declared pressure.

The economy of working at high pressures can be at once recognised by the following considerations.

A load of W watts, originally supplied at a pressure V, produces in the distributing mains a current $C_1 = W/V$.

If the resistance is r, the drop is Wr/V, and the ratio of this to V is $Wr/V^2 = p_1$.

When the pressure is made mV, the current for the same load is $C_2 = W/mV$, and the drop is $C_2 r = Wr/mV$.

The ratio of this to mV is $Wr/m^2V^2 = p_2$. Thus $p_2 = p_1/m^2$, and for a three-wire system where the voltage between outers

is double that of a two-wire system $m=2$, and the percentage drop with the same load is one quarter of what it was before.

Other ways of stating the effect of doubling the pressure while keeping the same drop are (1) that, assuming the same load, the conductors of the same length can be diminished to one-quarter of their former area, or (2) that, assuming the same load per yard run, the effective distance of supply from the feeding point could be quadrupled with the same distributors. The only drawback to these conclusions is that the current in the conductors is twice what it was before, and this would probably cause the current density to reach too great a value near the feeding points.

A cognate example has already been discussed, where a main fed at one end only is subsequently fed at both ends, when its section can be reduced to one-quarter.

Radius of Supply with Three-wire Systems.

In a three-wire system the bulk of the feeders (usually two-thirds of the number) consist of two conductors only, the sections of which are determined by Kelvin's law of current-density, and the total load they have to carry. Compared with a two-wire system, they can efficiently supply an area of twice the diameter, measuring between the two most remote feeding points, if worked at the same current density.

For instance, with a 200-volt two-wire supply, the effective radius of feeding (L) in yards is given by $L=\dfrac{Kv}{2D}$, where v is the drop and D is the economic current-density. Usually the drop v is taken as about 10 per cent. of the declared pressure, so that with 200-volt supply it would be 20 volts. If the economic current-density D is 1,000 amperes per sq. in., L would be 400 yards. This figure is frequently exceeded (but with a diminution of economy) by employing a lower current-density or with an increase of difficulty in pressure regulation by running with more than 10 per cent. drop at full load in the feeders.

Comparing a feeder of a given cross-section on a 200-volt two-wire system and one of the same size on a 400-volt three-wire system, we see that the effective radius of supply could be doubled, with the current-density and percentage drop the

same in both cases.   The three-wire feeder could also supply double the load in kilowatts, but the actual C^2r losses would then also be doubled.

In comparing the relative volumes of copper in the feeders on the two systems we will assume equal lengths and loads supplied, and that the current densities are the same, being fixed by Kelvin's law.   The current in the two-wire system is $W/V = C_1$ and in the three-wire system $W/2V = C_2 = \frac{1}{2}C_1$ and thus the section of copper in the latter will be half that in the former.   The actual voltage drop will be the same in both as $Cr = \frac{1}{2}C \cdot 2r$, but the percentage drop and the energy or C^2r losses on the three-wire will be half that in the two-wire system.

Saving in Copper with Three-wire Systems.

In the distributors, if current density be for the moment disregarded, a three-wire main working on the same pressure at the lamp terminals as with two wires, would have cross-
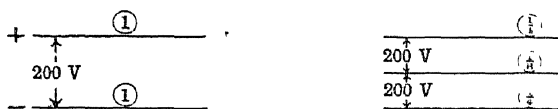
FIG. 46.

sections of only one-quarter of the latter   The middle wire is commonly made 50 to 60 per cent. of the outers, which gives it sufficient elasticity.

On these assumptions, the relative amounts of copper would be as represented in Fig. 46.   The saving would, therefore, be $(1+1) - (\frac{1}{4} + \frac{1}{4} + \frac{1}{8}) = 1\frac{3}{8}$, or 68·8 per cent. of the copper in the two-wire conductors.

The relative energy losses in two and three-wire distributors dimensioned, as in Fig. 46, are as follows :—

For the load W, on two wires $C = \dfrac{W}{V}$,

and the drop $\qquad v = \dfrac{2CL}{Ks} = \dfrac{2L}{Ks} \cdot \dfrac{W}{V}$,

and the energy losses are $\qquad C^2r = \dfrac{2L}{Ks} \cdot \dfrac{W^2}{V^2}$.

With three wires the voltage is 2V, and the cross-section neglecting the middle wire is $\frac{1}{4}s$. The current is $\frac{W}{2V}$; the drop is $\frac{2L}{K \cdot \frac{1}{4}s} \cdot \frac{W}{2V} = \frac{4L}{Ks} \cdot \frac{W}{V}$, double the former value, but preserving the same percentage of the supply pressure as before.

The energy losses are

$$\left(\frac{W}{2V}\right)^2 \cdot \frac{8L}{Ks} = \frac{2L}{Ks} \cdot \frac{W^2}{V^2},$$

the same as before.

The current density near the feeding points for two-wire is $\frac{W}{Vs}$, and for three-wire is $\frac{W}{2V} \bigg/ \frac{s}{4} = \frac{2W}{Vs}$, which is double the former.

If the comparison of volumes of copper be made with equal current densities at the feeding ends, where they reach their maximum values, the relation would be as in Fig. 47.

Fig. 47.

The saving in this case is $2 - 1\frac{1}{4} = \frac{3}{4}$, or $37\frac{1}{2}$ per cent.; or, taking the average of the two as approximating to working conditions, it can be stated as approximately 50 per cent.

When a comparison is made of the total costs of three *versus* two wires—that is, including the insulation and laying of the third conductor and the extra expenses of disconnecting boxes and control gear—the actual saving may be a good deal less than 30 or 40 per cent.*

In calculating the cross-sections of a three-wire system, or in working out any other problem connected with its network, the simplest plan is to consider it as a two-wire system at double voltage, ignoring the third wire, the section of which can be adjusted afterwards to about 50 per cent. of an outer conductor. Numerical examples on this point are given in Part I., Chap. II.

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* For a more detailed account of this question and the expression of many divergent views on it, *see* "Proc." Mun. Elec. Assocn., 1902. Paper by J. F. C. Snell, and Discussion.

Although neglected in the calculations, the function of the third wire is of great importance. Unless balancing is done systematically and thoroughly, the current in certain portions of it may cause a greater drop of pressure than that experienced in the outers, and may even injure the cable in places by overheating.

As an example of the effect of out of balance conditions, we will take the case of a 400 yd. irregularly loaded three-wire distributor on a 2×200 volt system. Each outer is 0 1 sq in with neutral 0 05, and the average load is equivalent to 50 amps. on each side, at the far end. The resistance of 400 yd. of 0·1 is 0·10 ohms, and of 0 05 it is 0·2 ohms When running balanced the drop on either side is 50 amps. $\times 0·1 = 5$ volts, which is satisfactory, since 4 per cent. of 200, or 8 volts, is permitted If there is 25 per cent. out of balance the drop on the heavily loaded side would now be 62·5 amps. $\times 0·1 = 6·25$ volts, and to this must be added the drop in the neutral 12 5 amps $\times 0·2 = 2·5$ volts, or, altogether, 8 75 volts, which is beyond the legal limit. To remedy this, if a permanent condition, the sections of the mains would have to be increased, or steps taken to adjust the balance.

Balancing.

To secure an equality between the loads on the two sides of the system, and therefore equal pressures, it should be a strict rule to connect motors of over 5 H.P. capacity, and even smaller, if liable to overloads, to the outer mains only. In this way the greatest cause of voltage irregularity is removed The lighting consumers should be carefully balanced on each side, and in this process there are three important factors : (1) Equality of the sum of the maximum demands ; (2) relative positions of the positive and negative services; and (3) the incidence of the consumers' peak loads.

It is customary in balancing to deal independently with the loads in each short street or section of a long street, and this covers the second condition fairly well ; but if, for instance, there be two large late closing establishments at some distance from each other, a large current will necessarily flow in the neutral between them, although the section would seem, on paper, to be well-balanced. Thus + and — services of the same class as regards their hours of burning should be tapped off as closely as possible to each other, although this is not easy to ensure.

The first condition as to numerical equality of the two sides in any one street can be fulfilled with great accuracy if demand indicators are in use, as their readings furnish

Distributor. High Street from South Street to Broad Street.

											Total	Class 1.	No. in street.	Name of consumer.	Class 1.	Total.											
Grand totals	Total	Class 6.	Total	Class 5.	Total	Class 4.	Total	Class 3.	Total	Class 2	(− side)	(− side)			(+ side)	(+ side)	Class 2.	Total.	Class 3	Total.	Class 4.	Total.	Class 5.	Total.	Class 6.	Total.	Grand totals
											6	6	10	A	4	4											
											9	3	3	B		6											
											10	1	5	C													
											14	4	9	D	2												
											16	2	14	E		11											
											19	3	22	F													
											26	7	21	G	5	16											
													6	H													
													8	I	5												
													12	J		20											
													15	K	4	23											
													17	L	3												

a good guide to the real simultaneous maxima. So desirable is this information that the instruments are well worth keeping in order for this function alone, even when discarded for tariff purposes. The times of incidence cannot easily be determined, but consumers can be divided into classes having approximately the same lighting hours, and a balance effected for each of these classes separately. A good sub-division for lighting consumers is (1) shops, (2) private houses, (3) public houses, (4) hotels and clubs, (5) churches, halls, theatres, public buildings, (6) offices and banks. Consumers in class (5) should be connected up on two balanced sides in all cases, so as to reduce the risk of total darkness in the event of panic or fire, or a breakdown of the supply on one side.

Various schemes for keeping the records have been devised, but the card system is probably the most flexible.   A specimen card with the methods of entering up is given on p. 123.

This plan enables one to see by a glance at the totals the polarity for the next service in the same class.   The grand total column indicates how closely the whole of the classes taken together is balanced.   In arriving at the grand totals, the class totals on the same line are all added and carried to the outside columns.   For simplicity's sake we have shown the consumers as all of one class, but in practice the entries would be scattered over the whole card, except in certain residential or purely shopping streets.

The actual entries to begin with are the estimated loads in amperes or equivalent standard lamps in the installations, but if demand indicator readings are available they should be used as soon as possible instead of the estimated loads

Pressure Regulation on Three-wire Distributors.

A bad balance is one of the greatest bugbears of the mains engineer, and is a frequent source of complaints as to pressure from consumers.   Too great care, therefore, cannot be taken in endeavouring to keep the balance cards or book quite up to date, and to follow the principles outlined above.   One of the best precautions to adopt is to be liberal in the number of three-wire services, and in the size of conductors and accessories where additional future load is to be expected   Under modern conditions the difference in cost between a three-wire service cable, joint box, and cut-out and the corresponding two-wire equipment is so small that a comparatively low limit of maximum demand should justify the former. The energetic manager is always pressing for new business in heating and cooking, and it is obviously preferable to subdivide these appliances on the positive and negative sides, if both are immediately available in the house.   In wiring large premises the supply inspector should insist on a rational subdivision of the circuits, so that the two sides are nearly balanced during the whole evening.   Thus, to take a private house, it is very bad practice, although common enough, to put the sitting rooms all on one side and the bedrooms, &c., on the other.

If a good proportion of three-wire services exists, it is always an easy matter to transfer, at the consumer's fuse boxes, a

portion of the load from the side with lower pressure to the other side. Portable voltmeter tests should be taken systematically on all the outlying portions of a network, with a view to applying these corrections. This should be done frequently, especially during the winter months, as consumers' load characteristics quickly change, and it takes but little to upset what was previously a good balance.

If proper attention is given to the balancing of each small section of the system the aggregate out-of-balance current on each feeder and on the station 'bus bars should be small. The converse is not necessarily true, for the sum of the positive and negative feeder currents may be practically identical, while very unequal pressures may exist at various points of the network. The ultimate effect can be controlled by the station engineer with the help of balancers and batteries ; but this does not entitle the mains department to assume that all is well outside, unless they actually test and correct the purely local irregularities.

Pressure Regulation at the Station.

The methods usually adopted for regulating the pressures on three-wire networks at the generating station are shortly described here, as they are so closely related to the distributing engineer's efforts towards the same object.

It must be borne in mind that, in many districts several of the feeders are necessarily of much greater length than the possibilities of a three-wire system would at first sight appear to warrant. It may be recognised that ultimately a separate high-pressure system will be required for the outlying districts ; but for the sake of uniformity of system, good plant load factor, and simplicity of running the high-pressure alternative is deferred as long as possible, especially in stations of moderate size.

The commonest arrangement is .to connect the generators across the outer wires, and to use a battery or balancers between either outer and the third wire, so that each side of the system can be independently regulated. In small stations the balancers usually work automatically, but in large stations they are mostly regulated by hand.

Another method of automatic balancing, but one which is scarcely ever employed in England, is that due to Dobrowolsky. The arrangement is to connect the neutral wire to the middle

point of the windings of a small auto-transformer of low resistance, which is supplied with alternating currents taken from a special machine by means of slip-rings.   The machine has a ring armature, and the two direct-current brushes are connected up to the outers of the three-wire system.

In some networks middle wires are run to every feeding point, while in others no middle wires at all are employed. Third wires are scarcely necessary on the short feeders, but in long feeders, if they are omitted, the effect of any out-of-balance current is largely accentuated, and the difficulty of regulation is correspondingly increased. The question depends a good deal on local conditions, but it will be found a safe practical rule to provide a middle wire in about one-third of the
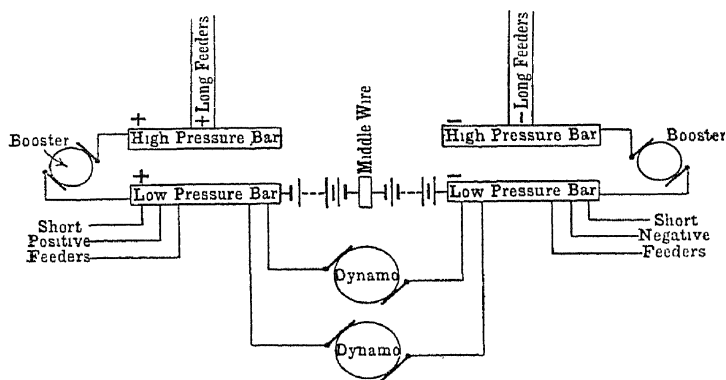

FIG. 48.

total number of feeders.   The long feeders may have to be specially boosted, and for this purpose are grouped on a separate pair of 'bus bars, to which two boosters are connected, as shown in Fig. 48.

There is another method of boosting, which can be arranged without special machines, and although not quite so straightforward, yet it admits of the pressures on the different bars and on both sides of the system being regulated very closely. Its chief feature is the cross-connecting of some of the dynamos between the high and low pressure bars, as will be seen in Fig. 49.   The machines marked A have each one pole connected to a high and a low bar respectively, while the C machines work as usual on the low bar, which supplies the group of short feeders.   If the highest working voltage of the

A dynamos is V, while the pressure between the low bars is V_L, there will be available between the high bars the pressure

$$V_h = V + V - V_L = 2V - V_L.$$

In contrast with this, the ordinary arrangement merely furnishes a possible high-bar pressure of V and a boosting effect
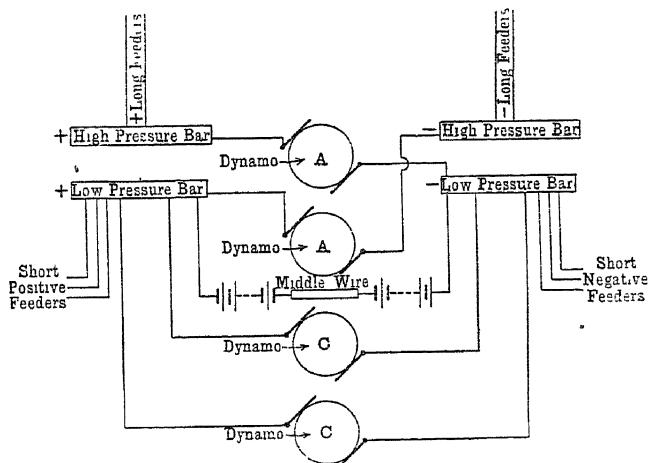

FIG. 49.

of $V - V_L$. The scheme of connections shown in detail in Fig. 50 will render the method clearer, and the following example will illustrate the amount of boosting available. With maximum machine voltage of 550 and a low-bar pressure of 500, $V_h = 2 \times 550 - 500 = 600$ volts on the high bar, and a boosting effect of 100 volts. By adjusting the pressures on the A
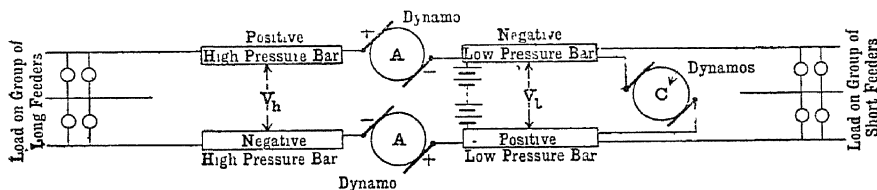

FIG. 50.

machines in conjunction with the batteries or balancers either side of the high bars can be regulated independently, this advantage being absent when the A machines are connected in the usual way to the high bars. One drawback will be noticed on referring to Fig. 50, and that is, in the event of a

short circuit on a C machine or one of the short feeders, there·
would be a pressure of about 1,000 volts between the high bars.

To ensure a good plant load factor and economy in running,
it is desirable to have as few different pressures as possible,
and thus it may be necessary to alter the resistance of one or
two of the feeders so that they may run in parallel with their
respective groups. With "solid" feeders this is not easy,
but on a drawn-in system an extra cable can be added for the·
whole or part of the length in order to increase the resistance.
A very convenient way of increasing the resistance is to employ
a loop of concentric cable connected up as shown in Fig. 51.

Such a device can also be used at the nearest feeding point
of a split feeder, Fig. 52 ; but the use of feeder resistances in
general must be looked upon as only a temporary expedient
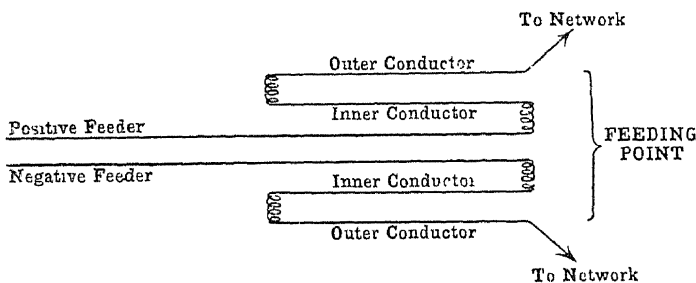before the loads have settled down to a steady state. The

FIG. 51.

requirements of districts sometimes vary greatly in summer and
winter, and the resistances of the feeders, and even the positions
of the feeding points, may have to be changed in the two seasons.

Technical Disadvantages of Three-wire System.

The chief drawbacks to the use of the three-wire system,
with continuous current, are the leakage troubles, which tend
to arise owing to the relative potentials of the conductors and
the surrounding soil. Even when all are carefully insulated,
and there is no artificial earth on the neutral, the condition of
electrostatic equilibrium is that the latter should approximate
to earth potential, and consequently the negative is always·
from 200 to 300 volts below it. This adjustment of potential
is in practice inseparable from British three-wire networks, as·
the B.O.T. insist on permanent earthing of the neutral through
a low resistance at the station, their chief reason being to·
minimise the chances of full voltage shock due to anyone

touching an outer pole while making a good earth, either with the other hand or with the feet. As will be explained later, this arrangement is strongly conducive to osmotic action on the negative wire whenever there is the slightest incipient weakness of insulation. Unless great care is taken and constant efforts are made to maintain a high insulation on all three wires, a larger proportion of faults must be expected, due to this electro-osmotic action, than with the simple two-wire system, and when they have to be located the methods are somewhat more troublesome and uncertain

Despite these facts, the balance of advantages is all in favour of the system, except, perhaps, for low-tension networks con-
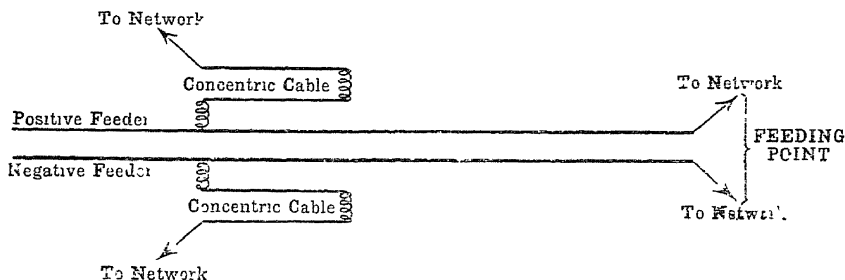

FIG 52.

sisting of small isolated areas round sub-stations, in which case a two-wire system is nearly as cheap.

Multi-wire Network.

If reference be made to this it is now more on account of its historic than of its practical interest.

By the use of five wires, for example, the feeding pressure can be quadrupled, while still retaining the same declared pressure between consumers' terminals. In spite of the great apparent saving of copper, the system is not now appreciably used on account of the switchboard complications and the difficulties in laying and jointing the mains, and in preserving a balance on the four " sides."

As soon as the Board of Trade permitted the use of 2×250 volts the chief *raison d'être* of the five-wire system disappeared. Although many misgivings were felt when metal filament lamps were first introduced, on account of the fragility of the high-voltage type, this difficulty having now been quite overcome, there is no reason why the pressure in any new three-wire scheme should not be standardised at 2×250 volts.

E. M D. S   T

CHAPTER X.

ALTERNATING AND POLYPHASE NETWORKS.

Alternating Currents.   Fundamental Formulæ.

In the calculation of alternating current mains some new factors have to be considered.   To the mains engineer, employing underground cables on modern systems, many of these produce such slight effects as to be merely of academic interest, and their theory will not be treated in any sense completely.

We assume that the reader is reasonably familiar with the elements of the theory of alternating currents, more especially the modification of Ohm's law for A C., and the rules for dealing with the vectorial quantities characteristic of A.C. circuits. The fundamental equation for an A C circuit is given for reference

An alternating E M.F., E, produces a current C in a circuit of impedance Z,

$$C = \frac{E}{Z} = \frac{E}{\sqrt{R^2 + X^2}}.$$

R is the ohmic resistance, and X is the reactance of the circuit in ohms.

$$X = \left(2\pi n L_s - \frac{1}{2\pi n K_c}\right) \text{ where } n \text{ is the frequency,}$$

L_s is the co-efficient of self-induction in henrys, and
K_c is the capacity of the circuit in farads.*
When there is no capacity in an inductive circuit

$$C = \frac{E}{\sqrt{R^2 + (2\pi n L_s)^2}},$$

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* L and K are the usual symbols for self-induction and capacity, but we have already used them in all the preceding formulæ as L=length and K=resistivity constant for copper   Thus we adopt the slight modification of L_s and K_c, which suggest sufficiently the standard symbols.

and for a non-inductive circuit with only capacity and resistance,

$$C = \frac{E}{\sqrt{R^2 + \left(-\dfrac{1}{2\pi n K}\right)^2}}.$$

The simple algebraic expressions for the D.C. circuit speedily become unwieldy for the A.C. circuit, unless special methods are employed.

A good practical example of the vectorial method is the case of two inductive circuits in parallel, common enough in distribution systems.

With D.C. if r_1 and r_2 are the resistances, and C_1 and C_2 the currents in the two branches, the joint resistance of the two in parallel is $\dfrac{r_1 r_2}{r_1 + r_2}$, and $C_1 \times r_1 = (C_1 + C_2) \times \left(\dfrac{r_1 r_2}{r_1 + r_2}\right)$, as the voltage drops between the two junctions reckoned either way must be equal.

Thus
$$\frac{C_1}{C_1 + C_2} = \frac{r_2}{r_1 + r_2}$$

The corresponding formula with two A.C. inductive circuits is
$$\frac{C_1}{C_1 + C_2} = \frac{Z_2}{Z_1 + Z_2},$$

where we replace the simple resistances r_1 and r_2 by the impedances Z_1 and Z_2

If R_1 and X_1, R_2 and X_2 are the ohmic resistances and reactances in the two branches,

$$Z_1 = \sqrt{R_1^2 + X_1^2} \text{ and } Z_2 = \sqrt{R_2^2 + X_2^2}.$$

In obtaining the sum of Z_1 and Z_2 it must be remembered that they are vector quantities, and to determine the arithmetical value of their sum or resultant, we must take into account their relative directions, which are shown in the diagram (Fig. 53).

OA drawn to scale represents Z_1, AB represents Z_2, and the resultant is given by OB.

But OA itself is the resultant of the vector OD or R_1, and the vector AD $=$ CE or X_1 at right angles to it.

Similarly AB is resolved into the two vectors $R_2 = AC$ or DE, and $X_2 = BC$.

We see at once that
$$OB^2 = (OD + DE)^2 + (CE + BC)^2$$
$$= (R_1 + R_2)^2 + (X_1 + X_2)^2,$$

and
$$OB \text{ or } Z_1 + Z_2 = \sqrt{(R_1 + R_2)^2 + (X_1 + X_2)^2},$$

and
$$\frac{C_1}{C_1 + C_2} = \frac{Z_2}{Z_1 + Z_2} = \sqrt{\frac{R_2^2 + X_2^2}{(R_1 + R_2)^2 + (X_1 + X_2)^2}}.$$

The important point to note in this example is, that vectors in the same direction such as R_1 and R_2, or X_1 and X_2, can be added arithmetically, but when in different directions like Z_1 and Z_2 they can only be thus added by resolving them into two sets of vectors, which are at right angles to each other. The same principle is again employed, when adding currents with different power factors
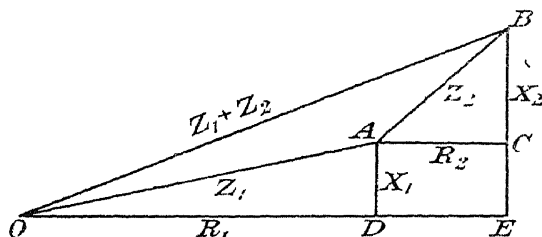

FIG. 53

An interesting example involving the use of the formula for parallel resistances was given in Mr. J. R. Beard's Paper ("Proc." Inst.E E., Nos. 253-255, 1916).

An underground cable of 0·15 section with $R_1 = 0·287$ and $X_1 = 0·137$ ohms per mile was worked in parallel with an overhead line also of 0·15 section with $R_2 = 0·287$ and $X_2 = 0·57$ ohms per mile.

The total current transmitted was 300 amperes and the current in the cable C_1 was given by

$$\frac{C_1}{300} = \sqrt{\frac{R_2^2 + X_2^2}{(R_1 + R_2)^2 + (X_1 + X_2)^2}},$$

or
$$C_1 = 300 \sqrt{\frac{(0·287)^2 + (0·57)^2}{(0·574)^2 + (0·707)^2}} = 210 \text{ amps.}$$

Similarly C_2 the current in the line was found to be 105 amperes. The two currents are not in phase (or their vectors

are in different directions), and hence their arithmetical sum
is more than the resultant current transmitted.

Alternating-Current Conductors.

In the ordinary two-wire single-phase circuit the conductors
themselves behave somewhat differently from those for direct
current. With high frequencies and large diameters of con-
ductor there is an increase in apparent resistance, due to what
is called the skin effect, or the tendency of the current to be
concentrated in the outer layers, thus diminishing the useful
cross-section of the conductor.

If the total current be regarded as the sum of a number of
independent current filaments, there will be less mutual induc-
tion among those in the outer layers than in the central, thus
tending to concentrate the flow of current into the outer layers
At frequencies below 50, and with sections less than 0·5 sq. in.,
this effect is negligible.

Another phenomenon resulting in a slight increase in appa-
rent resistance is that caused by the cables being made of
twisted wires, each layer of which forms a long coreless solenoid,
and gives rise to a weak magnetic field The magnitude of this
inductive effect is, however, one which need not be considered
in ordinary mains calculations, although it may reach appre-
ciable values with large cross-sections and high frequencies *

Effects of Capacity.

Dealing now with the arrangement of the conductors in
practice, the first desideratum is to avoid mutual induction
between them, and thus single-phase underground lines should
always take the form of concentric or two-core and triple-
concentric or three-core cables The magnetic fields produced
by the forward and return conductors respectively neutralise
each other, and the inductive drop in such a cable is small.

But by this construction the cable constitutes a good con-
denser, and, therefore, may give rise to very appreciable
capacity effects. The value of the capacity per mile in the
case of a simple concentric can be calculated from the formula,

$$K_c = \frac{0 \cdot 039k}{\log_{10} \frac{D}{d}} \text{ microfarads,}$$

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* It is possible, by lightly insulating the outer spiral conductors from
each other, to balance this last, known as the " spirality " effect, against
the skin effect, thus eliminating both.

where D is the internal diameter of the outer conductor and d the diameter of the inner conductor and k is the dielectric constant depending on the character of the insulating materials. It is usually more convenient to measure the actual capacity of lengths of cable similar to that proposed for any new work, instead of calculating it from formulæ.

Methods of measuring the capacity of various makes of cable are given in Chapter 11. (Part 11).

We may mention at once that in the practical calculation of A.C. conductors it is very difficult to deal with the effect of capacity by the formula for reactance,

$$\sqrt{R^2 + \left(2\pi n L, - \frac{1}{2\pi n K_c}\right)^2}.$$

Just as in all the methods used in D.C. calculations it is better to deal with currents rather than the corresponding resistances, so with capacity it is better instead of its reactance to deal with the current which would flow through it, when subjected to the working voltage. This current can be compounded vectorially with the load current, and the effect of the capacity on the line losses, voltage drop and power factor can then be determined.

The charging current of a single phase condenser is

$$V \cdot 2\pi n K_c 10^{-6} \text{ amps.}$$

(where K_c is in microfarads), and its phase is 90 deg. in advance of that of the voltage. This current is said to be wattless, as it absorbs practically no power. No account need be taken of capacity in ordinary distributors, as its value is too small in comparison with the magnitude of the load currents and ohmic resistances in circuit. In long underground trunk lines at high pressures, however, it is the source of various phenomena of considerable importance. In regard to regulation it is beneficial, as it tends to counteract the low-power factor due to the inductive loads, which are always met with in practice.

Dielectric Hysteresis.   Losses in Lead and Armour.

The presence of capacity may cause a real loss of power due to the so-called dielectric hysteresis in the dielectric of high-tension feeders, and for certain kinds of insulation the effect

·is such as to contribute something substantial to the sum of the total transmission losses. In other words, the condenser current, far from being wattless, or with a power factor of zero, may have a power factor which varies from 0·02 to 0·1 according to the nature of the dielectric. A good approximate rule for its value with the ordinary paper-insulated cable is to take the capacity current as having a power factor of 0·028.

Extra high-tension cables should preferably not be armoured, as the armour appreciably increases the impedance of the cable and causes an additional loss due to hysteresis and eddy currents. For two armoured cables 12 in apart the impedance is about three times the ohmic resistance, with a frequency of 60, and from 1 7 to twice the ohmic resistance with a frequency of 25.* The eddy current loss in the lead sheath, although measurable, need not be considered with modern low frequencies.

In distributing mains with their low pressures the dielectric loss can be disregarded Its aggregate amount in a typical system with high-tension and low-tension distribution, in comparison with transformer and meter losses, is discussed very fully in a Paper by Constable and Fawssett ("Proc." Inst. E E , June, 1903). For measurements of dielectric hysteresis and power factor of cables, *see* Part II. (Chaps. I. and II.).

Inductive Loads.

In adapting the principles already established to alternating distribution the other important new factor is that of inductance. In the mains themselves this quantity is usually small, but the consuming devices house-wiring, arc-lamps and especially induction motors, all tend to render the system inductive. The effect of induction alters the standard D.C. formulæ in certain important particulars.

The power supplied by a direct current, C, at a pressure V, is $P = CV$, and the R.M.S. value of the alternating current to supply this power at the same pressure would be identical if the circuit were non-inductive or with a power-factor of unity. But if the load be inductive, as, for instance, an arc-lamp or motor, the current would have a greater value C_0, where $C = C_0 \cos \varphi$. Cos φ is termed the power-factor, and φ is the

* THE ELECTRICIAN, Aug. 27, 1909 J B Whitehead. "Proc." Am I E E.

angle that represents the difference of phase between the current and voltage vectors. Thus $P = V . C_0 \cos \varphi$, or $C_0 = \dfrac{P}{V . \cos \varphi}$, and for the "load currents" corresponding to the loads, it is seen that on alternating-current supply the values are higher than on direct-current in proportion to $\dfrac{1}{\cos \varphi}$. In ordinary distribution there is a very great diversity in the phase differences which the various kinds of load tend to produce. The actual value, observed at the station or point of supply, is that of the vectorial resultant obtained by adding the vectors of the individual loads —for example, glow lamps with $\cos \varphi = 1$, induction motors running light with $\cos \varphi = 0.5$, and similar motors fully loaded with $\cos \varphi = 0.9$.

Where several loads of different power-factors are connected to the same point of supply, the resultant power-factor is found as follows :—

Let the loads be W_1, W_2, W_3, &c., with power-factors of $\cos \varphi_1$, $\cos \varphi_2$, $\cos \varphi_3$, &c.

Then the resultant power-factor $\cos \varphi_r$, by the ordinary trigonometrical rules, is such that

$$\tan \varphi_r = \frac{W_1 \tan \varphi_1 + W_2 \tan \varphi_2 + W_3 \tan \varphi_3 + \text{, &c.}}{W_1 + W_2 + W_3 + \text{, &c.}}$$

The tan φ values can be at once found from the tables corresponding to the $\cos \varphi$ values, and similarly $\cos \varphi_r$ when we have calculated $\tan \varphi_r$.

As an example let $W_1 = 200$ kw., $W_2 = 100$ kw., $W_3 = 50$ kw., and $\cos \varphi_1 = 0.7$, $\cos \varphi_2 = 0.8$, $\cos \varphi_3 = 0.5$.

The corresponding values of the tangents are $\tan \varphi_1 = 1.0176$, an $\varphi_2 = 0.75$, $\tan \varphi_3 = 1.732$,

and $\tan \varphi_r = \dfrac{200 \times 1.0176 + 100 \times 0.75 + 50 \times 1.732}{200 + 100 + 50} = 1.013$,

Cos φ_r for the same angle φ_r is 0.692, which is the resultant power-factor.

Drop with Inductive Load. Size of Conductors.

To find how the power-factor of the load affects the drop in a *non-inductive* single-phase main, and consequently its cross-section, it is best to represent the quantities in a vector diagram.

In Fig. 54 AC is the current vector lagging behind the voltage vector AB by an angle φ_1, while the length of AB represents the line pressure at the generating station or point of supply, V_1. If now BD be drawn parallel to the current vector (with which it must always be in phase), and equal to the arithmetical value of the drop $C_0 r$, the length and direction of AD will represent the pressure at the far end of the line, V_2.

The true voltage drop is the arithmetical difference between AB and AD or $V_1 - V_2$. The problem is usually to find the supply end voltage and the drop, when we know the load P at the far end of the line, its power-factor $\cos \varphi_2$, and the actual pressure V_2, which has to be maintained there.
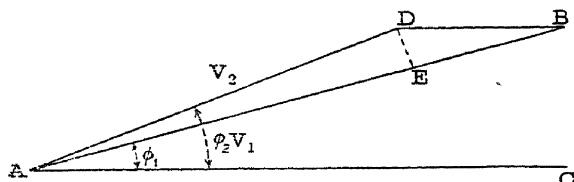

Fig. 54

From the ordinary trigonometrical rule we have the following relation between AD or V_2, AB or V_1, and DB or $C_0 r$,

$$V_1{}^2 = V_2{}^2 + (C_0 r)^2 + 2 V_2 C_0 r \cos \varphi_2.$$

If the load were non-inductive P would be $CV_2 = C_0 \cos \varphi_2 V_2$
Thus $C_0 = \dfrac{C}{\cos \varphi_2}$, and by substitution, and a trigonometrical transformation we obtain

$$V_1 = \sqrt{(V_2 + Cr)^2 + (Cr \tan \varphi_2)^2}.$$

Under non-inductive conditions $V_1 = V_2 + Cr = \sqrt{(V_2 + Cr)^2}$, with induction present it is slightly greater, but the effect of $(\tan \varphi_2)^2$ is so small as to be usually negligible. Thus the difference between V_1 and V_2, or the voltage drop, may be taken as the same in both cases. Hence, for a given voltage drop, in working out the cross-section of an A.C. feeder, of length 2L (forward and return), supplying a current C_0 with a power-factor $\cos \varphi_1$, we have only to replace C in the formulæ by $C_0 \cos \varphi$.

Thus $s = \dfrac{2CL}{Kr}$ becomes $\dfrac{2C_0 L}{Kr} \cdot \cos \varphi.$

Correspondingly, for a uniformly loaded distributor, with each conductor of length L,

$$s = \frac{CL^2}{Kv} = \frac{C_0 L^2}{Kv} \cdot \cos \varphi.$$

Inductive Loads on Mains with Inductance and Capacity.

The data for problems involving these factors are usually (1) a given load P, (2) a standard pressure V_2 at the load end, (3) a fixed percentage power loss p in the line. The cross-section is first determined from the permitted line loss, and the voltage drop is then calculated as follows The power supplied $P = V_2 C_0 \cos \varphi_2$, and as P, V_2 and $\cos \varphi_2$, the power factor of the load are all known, C_0 is at once found   The power loss is $pP = w = C_0^2 r$, where r is the ohmic resistance of the circuit ; and as $r = \dfrac{L}{Ks}$, $w = \dfrac{C_0^2 L}{Ks}$ and $s = \dfrac{C_0^2 L}{Kw}$.

In addition to the ohmic drop, we have with overhead lines, and to a less extent with underground cables, the effect of
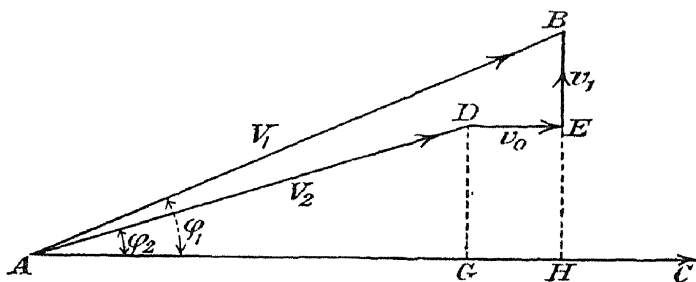

FIG. 55.

their inductance to consider. The ohmic drop is as before, $v_0 = C_0 r$ volts , the inductive drop, also in volts, is given by the expression $2\pi n L_s C_0$, where L_s is the coefficient of self-induction of the circuit in henrys.

The diagram in Fig. 55 is constructed by taking AC as the direction of the current vector C_0, and AD, representing to scale V_2 and making with AC the angle φ_2. The ohmic drop $v_0 = C_0 r$ being necessarily in phase with C_0 is represented by DE, to scale, parallel to AC.

The inductive drop v_1 or BE in the diagram has its length equal to $2\pi n L_s C_0$. It is at right angles to DE as it has a

relative phase displacement of a quarter period. Joining A to B gives the magnitude of the supply end pressure V_1 and its phase relation to the current. The cosine of the angle φ_1 which it makes with AC is the power factor at the supply end.

From the diagram

$$AB = \sqrt{\overline{AH^2 + BH^2}}$$
$$= \sqrt{\overline{(AG + DE)^2 + (DG + BE)^2}},$$

or $\qquad V_1 = \sqrt{(V_2 \cos \varphi_2 + C'_0 r)^2 + (V_2 \sin \varphi_2 + 2\pi n L_s C_0)^2}.$

All these quantities are known and thus V_1 can be calculated ; and we then find the true line drop $V_1 - V_2$.

The power factor at the supply end is

$$\cos \varphi_1 = \frac{AH}{AB} = \frac{V_2 \cos \varphi_2 + C'_0 r}{V_1}.$$

The power put into the line is $P_1 = V_1 C_0 \cos \varphi_1$, or by adding the line losses to the load it can be alternatively expressed as $P_1 = V_2 C_0 \cos \varphi_2 + r C_0^2$.

The coefficient of self-induction L, *per mile of conductor* of a paper-insulated multicore cable is obtained from the formula

$$\left\{ 0\ 085 + 0 \cdot 74 \log \left(\frac{d}{r} \right) \right\} 10^{-3} \text{ henrys,}$$

where d is the distance between centres of the conductors and r is the radius of each conductor.

A similar formula holds for overhead lines, but it is somewhat beyond our immediate purpose to show how these expressions are derived

When the length of the line from the point of supply to the load is M miles and L_s per mile is known, the value of

$$v_1 = 2\pi n L_s \times 2M \times C_0,$$

as the total length of conductor, forward and return, is 2M. In the same way in reckoning r in the formula for v_0 we must use 2M miles as the value of L.

When capacity exists in the line the charging current through it leads to some modifications in the formulæ.

If K_c is the capacity in microfarads of the transmission cable considered as a condenser, the charging current is

$$C_k = 2\pi n V K_c 10^{-6} \text{ amperes.}$$

The voltage V varies from the supply to the load end, but the total drop being generally less than 10 per cent., it is accurate enough to take the value V_2 as applying to the whole line when calculating C_k. The diagram in Fig. 55 is modified as shown in Fig. 56. The line AC now represents the load current in magnitude as well as phase To compound with it the capacity current, AS, is drawn equal to the value of C_k and at right angles to the voltage vector AD, as the two vector quantities are in quadrature. By completing the parallelogram we obtain its diagonal AR, which represents the resultant current at the supply end in magnitude and direction.
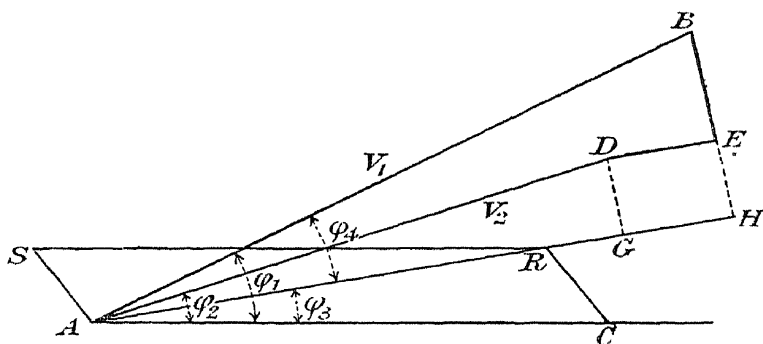

Fig 56

It can be at once calculated, since

$$AR^2 = AC^2 + AS^2 - 2AC \cdot AS \cos ACR,$$

or resultant current

$$C_r = \sqrt{C_0^2 + C_k^2 - 2C_0 \cdot C_k \cos(90° - \varphi_2)}.$$

To take a fairly accurate account of the capacity we have now merely to replace C_0 by C_r in the formulæ for finding V_1 and the other quantities required.

It will be at once noticed from Fig. 56, that the current at the supply end is less than before, due to the capacity of the line, and that the power factor has been improved, as φ_4, its phase angle, is less than the original φ_1, without capacity in the circuit.

The benefit of capacity of a moderate amount is clearly recognisable in this practical method of calculating its effect. Ohm's law for an A.C. circuit shows the beneficial influence

of capacity in another way. When inductance and capacity are *in series,* $V = C\sqrt{r^2 + \left(2\pi nL - \dfrac{1}{2\pi n K_c}\right)^2}$, and it is clear at once that when $\dfrac{1}{2\pi n K_c}$ approximates to $2\pi nL$, the quantity under the root sign will tend to become r^2, and we get $V = Cr$, which represents non-inductive conditions. When capacity and an inductive load are *in parallel,* as in A.C. lines and networks, its beneficial effect is not so simple to indicate algebraically, but the vectorial addition of the capacity current in the method we have used above, illustrates the general effect clearly.

Power Loss in Alternating Mains.

Although the lagging current may produce but little effect on the drop, it is quite another matter when the loss of power in the line is considered

The line current being C_0 (or C, when capacity is present) the watts lost in transmission are

$$w = C_0^2 r, \text{ and as } C_0 = \frac{C}{\cos \varphi} \cdot \quad w = r \cdot \frac{C^2}{\cos^2 \varphi}.$$

Thus, the section necessary for the current C under non-inductive conditions would have to be increased in the proportion $1/\cos^2 \varphi$ for the same percentage loss of power in the line when dealing with a load having a power factor of $\cos \varphi$.

This effect is one of the chief disadvantages in the distribution of alternating currents at low pressures The worse the power factor the greater is the actual current in the mains as compared with non-inductive conditions, and consequently the higher is the heating loss. It may seem, at first sight, curious that the drop is not increased corresponding to the heat loss, but on reference to the diagram (Fig. 54) it will be recognised that the higher power factor at the supply end represents the extra power required for this loss, and the drop is scarcely altered by the inductance of the load. The power factor of a distributing system inclusive of the consuming devices must be estimated as a preliminary to designing a new main. If the magnitude and phase difference of each load are known, the resultant power factor can be determined by the formula

already given. The resultant value may vary within wide limits from hour to hour, but the value at or about full load is the most important. Further, it should not be overlooked that, in daylight hours, when many lightly loaded transformers and motors are in circuit and the power factor is consequently low, the heating loss in the mains may reach a substantial figure

For mixed circuits of incandescent lamps, arc lamps and motors approximate values can be estimated from previous experience, and in such cases cos φ will range from 0·8 to 1. Where induction motors preponderate the value will be less—*i.e.*, from 0·7 to 0·9, depending on the proportion of full load they are taking. Where it is possible to insert a wattmeter in the circuit and at the same time take observations of the current and pressure, the relation of true watts to apparent watts, or cos φ, can be easily obtained. An extreme case of low power factor is seen in the charging current, when testing long high-pressure mains. Very little true watts are required, since the power factor is only 0·028, but large generating units must be used on account of the magnitude of the current, which, as we have seen, is directly proportional to the pressure

The volume of copper required in a single-phase system with non-inductive mains and loading is identical with that for direct current with the same pressure drop. With a bad power factor the drop would not differ much from that of a non-inductive system, but with a load heavy enough to necessitate attention being given to the current density, the sections of the mains might have to be increased on an alternat-

ing-current system, since $C_0 = \dfrac{C}{\cos \varphi}$.

The fact that the maximum instantaneous value of the voltage is $\sqrt{2}$ times the R.M.S. value, and thereby increases the stress in the dielectric, might be supposed to add to the cost of insulation, but the factor of safety is so high with low-tension cables that they are just as well adapted for the same declared pressure on alternating current as direct current, and there is no additional cost due to their being sold for alternating systems.

In the high-tension feeders this $\sqrt{2}$ factor has to be considered by the designer in proportioning the dielectric. (*See* Chapter IX., Part II., " Extra High-Tension Cables.")

Three-phase System.

The well-known facilities which the three-phase system affords for the supply of motive power has, in recent years, tended to its rapid extension in industrial districts for combined lighting and power.

The single-phase system, although used for power supply to a surprising extent still, on account of the retention of established conditions, has the disadvantage of causing heavy rushes of current on starting up motors, and thus interfering with the voltage regulation.

Three conductors at least are necessary in the distributing mains for three-phase, the generators being wound so as to supply three currents, whose phase difference between each pair is 120 deg.

Three-core cables, in which the insulated conductors are twisted together, with a lay of about twenty times the pitch diameter, are now universally employed for three-phase currents. This symmetrical arrangement gives practical immunity from inductive effects, and is superior to the older triple-concentric cables used for this purpose, in which the inductances were not completely neutralised.

The conductors and generators can be correlated in two different ways .—

1. The " star," in which the current through the generator coils is the same as that in each of the lines, whereas the voltage between any two of the latter is $\sqrt{3}$ times the voltage in any one of the three sets of generator coils.

2. The " mesh," or Δ, in which the voltage between any two lines is the same as that in the generator, while the current is $\sqrt{3}$ times that which flows in the generator coils.

Delta-wound motors can be used equally well on a star system, and vice versa.

The effects of capacity and induction are met with on three-phase systems, and their influence is similar to that already discussed for single-phase supply. There are important points of difference, however, in connection with the measurement of power, the determination of voltage drop and cross-sections of conductors which will now be described.

Measurement of Power in Three-phase Circuits.

With the star system and a *non-inductive load* (Fig. 57) the line current is C, the pressure between any two lines is V and that in the generator coils is V_1. Each of the three circuits contributes power equal to CV_1, and thus the total power $P = 3CV_1$. But as $V_1 = V/\sqrt{3}$, $P = CV\sqrt{3}$.
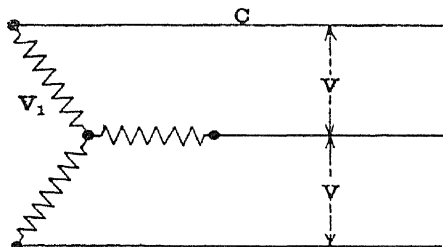

Fig. 57.

With the Δ connection (Fig. 58) the power is similarly $P = 3C_1V$, and since $C_1 = C/\sqrt{3}$, $P = CV \cdot \sqrt{3}$, as before.

Thus, with either mode of connections the rule for power measurement from observations of the line voltage and current is the same, with balanced loads. If the loads are *inductive* and the power factor is not known, the power must
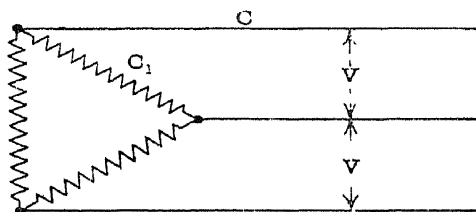

Fig. 58.

be measured either by a wattmeter or by the three-ammeter or three-voltmeter method. These are described in any book on alternating currents.

Three-phase Four-wire Distribution.

When lighting and power are taken from the same mains the use of three-phase currents with four wires is for several reasons preferable to either of the arrangements just illustrated.

The scheme of wiring is given in Fig. 59, from which it is seen that the lighting services are taken off each live conductor and the neutral wire, which is fed from the middle point of the star windings, while the motors are connected to the three lines. Under these conditions the neutral wire serves only for purposes of balancing inequalities in the loads of the respective groups of lamps, just as it did in the three-wire direct-current system. Since the sum of the instantaneous values of three equal three-phase currents, which meet in the middle wire, is zero, there will normally be very little current flowing in that wire if the balancing is done effectively. Similar statistics of the respective loads must be kept, as already described for the three-wire system, but in the present case the object aimed at is to secure an ultimate equality between
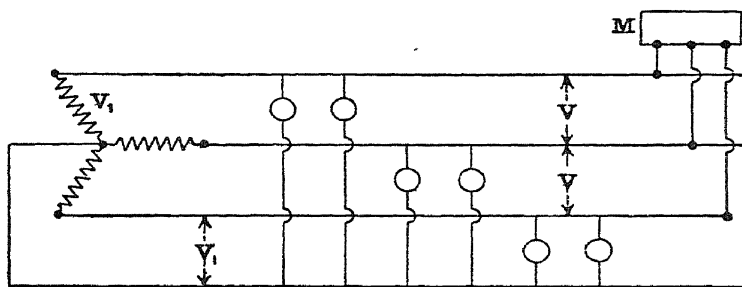

Fig 59

each of the three " sides " instead of two, so that rather more care is necessary, if each section of main is to be well-balanced.

The Δ system of supplying three-phase currents does not lend itself to the use of the fourth or neutral wire, but naturally if either the Δ or simple star system with three wires is employed for combined lighting and power the lamp loads between each pair of wires must be equalised. As motors take the same current from each wire they do not affect the balancing problem of any of the alternatives. The great advantage of the four-wire method is the possibility that it affords of working at a higher voltage in the distributors with the proportionate saving in copper which that implies. The voltage on the incandescent lamps defines the limits for three-phase working just as with other methods. Where no

fourth wire is employed, the pressure on the lamps must be the same as that on the motor windings. But in Fig. 59 it will be seen that the motors are connected across the three phases only at the higher working pressure V, whereas the lamps run at the lower voltage V_1. If V_1 be fixed as high as possible— *i.e.*, 240 to 250 volts—V will be $V_1\sqrt{3}$, or 1·7 times what it was when three wires only were used. The proportion of copper required for the motive power can thus be reduced to $1/\sqrt{3}$ with equal current densities. It will be shown later that the volume of copper is also diminished in respect of the lighting load.

The four conductors requisite for this system are built up symmetrically into a four-core cable, which is practically non-inductive. In its construction less filling material is necessary than in a three-core cable, prior to pressing on the lead sheath. It is very convenient for servicing, as the same size of box can be used as with a three-core main, and there is but little increase in the cost of disconnecting boxes, &c., on a four-core system.

In dealing with power measurements care must be taken to define the voltage that is meant. Based on the actual lamp voltage the power taken is $P=3CV_1$, but if on the full-phase voltage as before $P=C.V.\sqrt{3}$.

Inductive Three-phase Loads. Line Losses.

In what precedes, the load has been assumed to be non-inductive, but if it actually has a power factor, cos φ, the same relations hold good as for single-phase systems.

Then the power $P=C_0V . \sqrt{3}$ cos φ—that is, if φ is equal for all three phases—which is approximate enough for the usual conditions. The power wasted in heating the mains is now $3C_0^2r$, where C_0 is the lagging current. But C_0 cos $\varphi=C$, or the current when inductance is absent, and, therefore,

$$\text{Power loss}=3C_0^2r=\frac{3C^2}{\cos^2\varphi} . r.$$

Thus the actual heating loss in the conductors is increased in the ratio $1/\cos^2\varphi$, and if it is desired to keep this loss at the same figure as with non-inductive loading, the cross-sections must also be increased in the ratio $1/\cos^2\varphi$.

Size of Conductors on Three-phase Systems.

All the formulæ and methods already given for single-phase are applicable to three-phase ; allowance has only to be made for the effects of the 120 deg. phase displacement of the currents in the wires. The cross-sections are usually calculated for a stated percentage loss p in the line at a given pressure, or they are based on the economic current density. If P is the power supplied, this is equal to $C_0 V \cos \varphi \sqrt{3}$, from which we can find C_0. The line losses are $pP = w = 3C_0^2 r$, where r is the resistance of *one wire*. Since $r = \dfrac{L}{Ks}$,

$$w = \frac{3C_0^2 \cdot L}{Ks} \text{ or } s = \frac{3C_0^2 L}{Kw}.$$

If the economic current density D is fixed, s is $\dfrac{C_0}{D}$.

We may note here the relative losses in three-phase and single-phase lines with equal pressures and the same cross-sections and loads. In three-phase

$$C_0 V \cos \varphi \sqrt{3} = P \text{ or } C_0 = \frac{P}{V \cos \varphi \sqrt{3}}.$$

$$\text{Line loss} = 3C_0^2 r = \frac{3P^2 r}{3V^2 \cos^2 \varphi} = \frac{P^2 r}{V^2 \cos^2 \varphi}.$$

In single-phase where C_1 is the current,

$$C_1 V \cos \varphi = P, \text{ or } C_1 = \frac{P}{V \cos \varphi}.$$

$$\text{Line loss} = 2C_1^2 r = \frac{2P^2 r}{V^2 \cos \varphi}.$$

This is double the loss for three-phase, but the volume of copper is less in the proportion of $2 : 3$. Consequently, if the volumes of copper are made equal by increasing the sections of the single-phase conductors by 50 per cent., the three-phase loss will be only 75 per cent. of the single-phase loss.

As regards the voltage drop in a three-phase circuit, it follows at once from the phase relation of the currents in any pair of wires differing by 120 deg., that the ohmic drop between them, if each wire is of resistance r, is $v = rC_0\sqrt{3}$. Therefore, if we take all the previous formulæ for single-phase circuits

and insert $r\sqrt{3}$ instead of the total circuit resistance r, the results will be perfectly valid for three-phase working. The vector diagrams, as given in Figs. 54 and 55 for single-phase, will be true also for three-phase if we bear in mind the following points.

The voltages V_1 and V_2 (Fig. 55) now represent the values between *any pair* of wires in the system, which is assumed to be balanced or nearly so. DE or v_0, the ohmic drop, will now be $rC_0\sqrt{3}$, r being the resistance of one wire, and similarly the inductive drop v_1 will be $\sqrt{3}$ times the inductive drop in one wire.

1. For *non-inductive* mains with *inductive* loads we found for single-phase $V_1 - V_2 = v = Cr = C_0 r \cos \varphi,$

and $\qquad s = \dfrac{2C_0 L}{Kv} \cdot \cos \varphi$ (L being the length of one wire).

Hence for three-phase under the same conditions we have

$$V_1 - V_2 = v = Cr\sqrt{3} = C_0 r \cos \varphi \sqrt{3},$$

and s becomes $\dfrac{C_0 L \cos \varphi \sqrt{3}}{K \cdot v}$. (L also being the length of one wire).

2. With *inductive mains and loading* we obtained the formula for single-phase

$$V_1 = \sqrt{(V_2 \cos \varphi_2 + C_0 r)^2 + (V_2 \sin \varphi_2 + 2\pi n L_s C_0 2M)^2}.$$

For three-phase we substitute $C_0\sqrt{3}$ for $C_0 r$, but r is now the resistance of one wire only, instead of the complete circuit. Similarly we substitute $2\pi n L_s C_0 M\sqrt{3}$ for $4\pi n L_s C_0 M$; L_s is the coefficient of self-induction per mile of conductor, and M is the length in miles from supply to load. Thus V_1 for three-phase becomes :—

$$V_1 = \sqrt{(V_2 \cos \varphi_2 + C_0 r\sqrt{3})^2 + (V_2 \sin \varphi_2 + 2\pi n L_s C_0 M\sqrt{3})^2}.$$

From this we obtain the drop $v = V_1 - V_2$.

3. The composition of the capacity and load currents follows the same procedure as in single-phase working.

If K_c microfarads is the Y capacity of the three-core cable, or the capacity of the imaginary condenser formed by one core and the sheathing, then the capacity current is

$$2\pi n K_c \frac{V}{\sqrt{3}} \cdot 10^{-6}.$$

When combined with C_0 it gives the value of C_r, which is substituted in any of the formulæ instead of C_0, if appreciable capacity effects exist.

This substitution in the single-phase or three-phase formula is not strictly accurate, since the value of the current varies from C_0 to C_r, along the line, owing to the distribution of the capacity. The average value of C_r and C_0 would give more accurate results when determining V_1, but usually C_r gives a close enough approximation The average value should be used in calculating the heating losses.

Further, the distributed capacity produces a varying phase angle between the vector of the ohmic drop and that of V_2. Except on very long lines, which must be calculated by less simple methods, this effect can be neglected without serious error.

We shall now illustrate the use of these formulæ by calculating an actual transmission line, but before doing so we may remark that the diagrams we have used in arriving at the formulæ can also serve as the basis for graphical determination of the quantities involved. If facilities exist for carefully working to scale, the graphical methods are simple in operation, but on the other hand, the magnitudes considered vary through wide ranges, so that it is not possible to get accurate results unless the scale of the diagram is properly chosen.

We shall assume the transmission to be by a three-phase cable, in the example, and if the working out is clearly understood, the calculations for single-phase will present no difficulty. The load, P, to be supplied is 1,500 kw with a power factor $\cos \varphi_2 = 0.8$, at a pressure of 10,000 volts, V_2, and a frequency, n, of 50 per sec. The distance from the supply station is 25 miles.

From the data available it is found that the economic current density D is 1,100 amps. per sq. in., and

$$C_0 = \frac{P}{V_2 \cos \varphi_2 \sqrt{3}} = \frac{1,500,000}{10,000 \times 0.8 \times \sqrt{3}} = 109 \text{ amps.}$$

Then the cross-section $s = \dfrac{C}{D} = \dfrac{109}{1,100} = 0.099$ or 0.1 sq. in. (nearest standard).

For a three-core 0.1 sq. in. 10,000 volt cable, the Y capacity is found from the cable-makers' tables as 0.4 microfarads

per mile. The total capacity K_c of the 25-mile line is, therefore, $25 \times 0.4 = 10$ microfarads.

The capacity current $C_k = 2\pi n K_c \cdot \dfrac{10,000}{\sqrt{3}} \cdot 10^{-6}$

$$= 2 \times 3.14 \times 50 \times 10 \times \frac{10,000}{1.732} \times \frac{1}{1,000,000} = 18 \text{ amps.}$$

The resultant current C_r is equal to :—

$$\sqrt{C_0{}^2 + C_k{}^2 - 2 C_0 C_k \cos (90° - \varphi_2)}.$$

As $\cos \varphi_2 = 0.8$ we find from the tables $\varphi_2 = 37°$, and $(90° - \varphi_2) = 53°$, and $\cos 53° = 0.6$.

Thus $C_r = \sqrt{109^2 + 18^2 - 2 \times 109 \times 18 \times 0.6} = 99$ amps.

The line pressure at the supply end is :—

$$V_1 = \sqrt{(V_2 \cos \varphi_2 + C_r r \sqrt{3})^2 + (V_2 \sin \varphi_2 + 2\pi n L_s C_r M \sqrt{3})^2}$$

These quantities in figures are :—

$V_2 \cos \varphi_2 = 10,000 \times 0.8 = 8,000$ volts.

$C_r \cdot r \cdot \sqrt{3} = 99 \times 0.44 \times 25 \times 1.732 = 1,886$ volts.

(r for 0.1 sq. in. is 0.44 ohms per mile).

$V_2 \sin \varphi_2 = 10,000 \times 0.6 = 6,000$ volts.

L_s per mile of conductor in a 0.1, 10,000 volt three-core cable is approx. 0.5 millihenrys and M is 25 miles.

Then $\quad 2\pi n L_s C_r M \sqrt{3} = 2 \times 3.14 \times 50 \times \dfrac{0.5}{1,000} \times 25 \times 1.732 \times 99$
$$= 678 \text{ volts,}$$

and $\quad V_1 = \sqrt{(8,000 + 1,886)^2 + (6,000 + 678)^2}$
$$= \sqrt{9,886^2 + 6,678^2}$$
$$= \sqrt{142,330,000} = 11,930 \text{ volts.}$$

Voltage drop in the line
$$V_1 - V_2 = 11,930 - 10,000 = 1,930 \text{ volts.}$$

The power loss is $3C^2 r$, where C is the mean of C_r and C_0,
$$= 3 \times 104^2 \times 0.44 \times 25 = 356 \text{ kw.}$$

The total power required at the supply end P_s is $1,500 + 356 = 1,856$ kw.

The percentage line loss is $\dfrac{356}{1,856} \times 100 = 19$ per cent., which is too high a figure for good regulation.

The improvement in power factor due to the capacity is apparent when we calculate $\cos \varphi_4$ (Fig. 56).

By adding the losses at the supply end to the load we know that P_s is 1,856 kw. But P_s also $= C_1 V_1 \cos \varphi_4 \sqrt{3}$, and thus

$$\cos \varphi_4 = \frac{1,856 \times 1,000}{99 \times 11,930 \times \sqrt{3}} = 0 \cdot 9.$$

Contrary to the conditions on overhead lines, the inductance of the cable has no great influence on the supply voltage. If we omit this factor, 678, volts and calculate V_1, it proves to be 11,560 volts. If capacity and inductance in the main are both absent the drop is $C_0 r \cos \varphi_2 \sqrt{3} = 109 \times 11$ ohms $\times 0 \cdot 8 \times 1 \cdot 732 = 1,660$ volts, and V_1 is 11,660 volts.

For absolutely non-inductive conditions the drop is

$$v = \frac{P_s}{V\sqrt{3}} \times r \times \sqrt{3} = \frac{1,500,000}{10,000} \times 11 \text{ ohms} = 1,650 \text{ volts, and}$$

V_1 is 11,650 volts.

The necessity for trying to keep a good power factor on the mains is so obvious that special devices are used for counteracting the effect of inductive loads and lines, when the power factor falls below a certain figure. The condenser effect of the cables being, in itself, generally insufficient, it must be supplemented with static condensers, or else leading currents must be obtained from running machines called synchronous condensers and phase advancers.

The latter method implies expensive machines and the cost of attention and maintenance. The static condenser has the advantage of requiring no attention, and it can be made to give a distributed instead of a local correction to the inductance of a main or load. The static condenser with this function was until recently considered to be only a laboratory type of apparatus, with a prohibitive cost. Now, however, there are on the market robust practical designs such as the oil-immersed condensers made by the British Insulated & Helsby Co., which are very efficient and reasonable in price.

As some power companies increase their charges for bad power factors, and conversely give a rebate for good power factors, it will certainly pay the consumer in such cases to consider the use of condensers.

Relative Economy of Single and Three-phase Systems.

As already mentioned there is a considerable saving in copper by the use of three-phase currents. In making a true comparison the following conditions must be observed : The power supplied, the declared pressure on the lamps and the percentage drop must be identical for any of the alternative methods.

The fundamental system for purposes of comparison is the single-phase two-wire, which requires the same volume of copper as the two-wire direct-current.

The three alternatives are represented in Fig. 60 (1, 2 and 3). The voltage V being the same throughout, the power supplied in (1) and (2) respectively is

$$P = C_1 V = C_2 V \sqrt{3}, \text{ or } C_2 = \frac{C_1}{\sqrt{3}},$$

while the corresponding drops are in (1) $2C_1 r$, and in (2), $C_2 r \sqrt{3} = C_1 r$, by substituting above.

(1) Single-phase.   (2) Three-phase Three Wires.
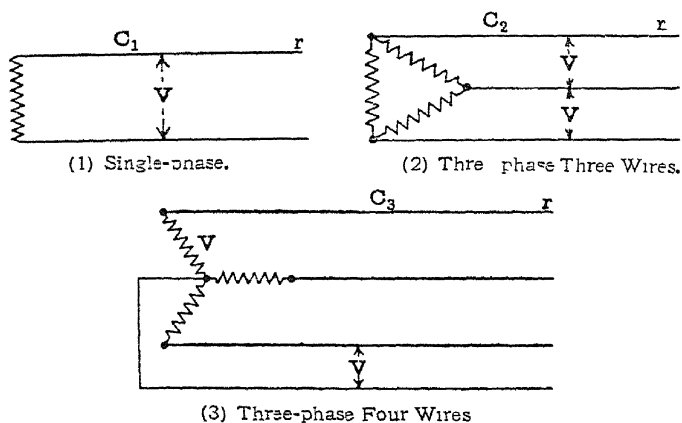
(3) Three-phase Four Wires

Fig. 60.

Thus the drop in (2) is half what it is in (1) when the mains are of the same section, and, consequently, only half the copper per conductor need be used to give an equal drop. The ratio of the total volumes of copper for equivalent conditions is therefore $3 \times \frac{1}{2} : 2 = \frac{3}{4}$ of that necessary for single-phase.

In comparing (3) with (1), $C_1 V = 3 C_3 V$, or $C_3 = \frac{1}{3} C_1$, the drops being in (1) $2C_1 r$ and in (3) $C_3 r$, neglecting the effect of the neutral current by assuming a perfect balance.

By substitution, $C_3 r = \frac{1}{3} C_1 r$ or, one-sixth of what it was in (1). The ratio of the volumes of copper (omitting the neutral) is therefore $3 \times \frac{1}{6} : 2 = \frac{1}{4}$, or, as in practice, when the neutral is equal in section to the other three conductors, $4 \times \frac{1}{6} : 2 = \frac{1}{3}$ of the amount for single-phase. As in the other analogous cases of comparing economies in copper, the current density limitation will modify the result if this is more important than the criterion of voltage drop alone. It is well to remember that there are no objectionable features in the four-wire three-phase system corresponding to those met with on the three-wire direct-current networks.

Osmotic action is entirely absent, on account of the current being alternating, even when the neutral is permanently earthed.

There is thus no tendency for faults to be produced due to this cause, and the trouble and expense of maintaining a sound network are substantially diminished.

Two-phase System.

No engineer designing a distribution scheme would now recommend a two-phase system. It exists in certain cases still as a survival of the transition period from single-phase to multi-phase, when the industrial supply of power as distinct from lighting began to assume prominence. In this system two currents are employed, differing in phase by 90 deg., and they may either form two entirely distinct circuits with four wires, or two of these may be replaced by one common return, thus reducing the conductors to three. In the transition period two of the existing single-phase concentric cables were sometimes arranged under the first alternative, thus avoiding capital outlay in copper and at the same time permitting the supply to motors which would have a good starting torque, but when the system was extended into new territory the common return was naturally preferred.

For the sake of completeness in this summary of the characteristics of the usual multi-phase systems, the following notes on two-phase are added :—

When four conductors are employed, the system has the same properties as two independent alternating current circuits each supplying half the power. In Fig. 61 (1, 2 and 3), the

two arrangements (1) and (2) are seen to be equivalent as regards power$=2C_1V$, drop$=2C_1r$, and volume of copper $=4l^2/Kr$, where l is the length of each conductor.

In (3) the following relations exist : The voltage between the two outer conductors is $V_3=V\sqrt{2}$, and the resultant current in the common return is $C_3=C_1\sqrt{2}$. The power transmitted in (3) is the same as before, viz., $2C_1V$, while the relative drops are as follows, the length of each main being the same in all cases.
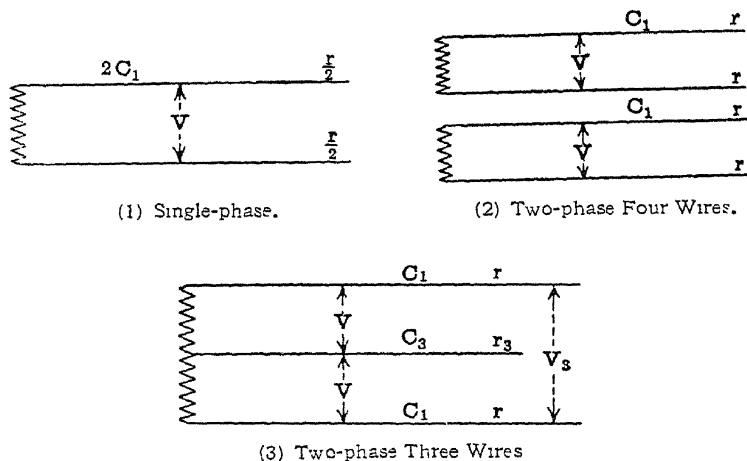

(1) Single-phase.

(2) Two-phase Four Wires.

(3) Two-phase Three Wires

FIG. 61.

In (1) $v_1=2C_1r$, and in (3) $v_3=C_1r+C_3r_3$. Since the current density has the same value in the common wire as in the two outers, $r_3=\dfrac{r}{\sqrt{2}}$, and $C_3=C_1\sqrt{2}$, and $v_3=C_1r+C_1r=2C_1r$.

The relative amounts of copper are :—

In (1) $\dfrac{4l^2}{Kr}$, and in (3) $\dfrac{2l^2}{Kr}+\dfrac{l^2\sqrt{2}}{Kr}=\dfrac{3 . 4l^2}{Kr}$,

that is to say, 85 per cent. of (1).

An inductive load has similar effects to those with single-phase, but in this case again it is sufficiently accurate to reckon the drop identical with that due to a non-inductive load. The

losses of power in the mains (when inductance is absent) are as follows :—

In (1) $\qquad$ $p_1 = 4C_1{}^2 r,$

in (3) $\qquad$ $p_3 = 2C_1{}^2 r + C_3{}^2 r_3$

$$= 2C_1{}^2 r + (C_1\sqrt{2})^2 \frac{r}{\sqrt{2}}$$

$$= 3\cdot 4\ C_1{}^2 r, \text{ or } 85 \text{ per cent. of } p_1.$$

If the specification demands equality in the amounts of power lost in both cases, the sections of the mains in (3) can all be 85 per cent. of their former values.

Where the load is inductive the heating losses will, as before, be increased in the ratio $\dfrac{1}{\cos^2\varphi}$, as compared with non-inductive conditions.

From a survey of these figures the reasons for the disuse of the system in favour of three-phase will be at once apparent.

Comparison of Distribution Systems.

For easy reference we summarise below the results we have found for the different systems, working under the conditions already described in detail :—

	Volume of copper.
Two-wire D.C. or single-phase A.C.	1 000
Three-wire D.C. or single-phase A.C.	0 312
Two-phase, separate circuits	1·000
Two-phase, three-wires	0 85
Three-phase, three-wires	0·75
Three-phase, four-wires	0·33
(Neutral equal to outers)	

The mains and loads are taken as non-inductive in every case

Analysis of Alternating-current Networks.

When loads of different power factors are connected to distributors or to the branches fed off a ring main, they must be treated as vectors, before the D.C. methods of analysis can be used. Any current C_0 with power factor $\cos\varphi$ can be resolved into $C_0\cos\varphi$ and $C_0\sin\varphi$, which are the energy and wattless components at right angles to each other. (The j notation for two axes at right angles is used by Steinmetz and others, instead of the method with $\sin\varphi$ and $\cos\varphi$ components.) At any point, where several currents meet, we have first to determine the two sets of vectorial quantities, and then com-

bine them according to the law of vector addition.   If C_0' is the arithmetical sum of all the cos φ vectors, and C_0'' the sum of the sin φ vectors, the value of the current in the line which they enter is

$$C_r = \sqrt{(C_0')^2 + (C_0'')^2}.$$

From the trigonometric rule for a right angled triangle the power factor of C_r or cos α is

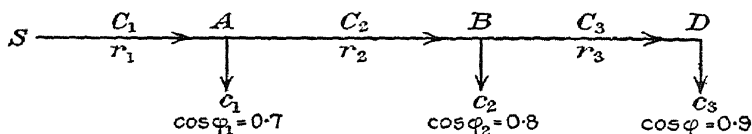$$1 \Big/ \sqrt{1 + \Big(\frac{C_0''}{C_0'}\Big)^2}.$$

Fig 62.

The method will be at once clear from the following example :—

In Fig. 62 we have three loads, c_1, c_2 and c_3, each of 100 amps., with power factors as shown, on a single-phase system. Resolving them along cos φ and sin φ axes we obtain .—

c_1 cos $\varphi_1 = 100 \times 0.7 = 70$, and c_1 sin $\varphi_1 = 100 \times 0.7 = 70$;
c_2 cos $\varphi_2 = 100 \times 0.8 = 80$, and c_2 sin $\varphi_2 = 100 \times 0.6 = 60$,
c_3 cos $\varphi_3 = 100 \times 0.9 = 90$, and c_3 sin $\varphi_3 = 100 \times 0.44 = 44$.

In Fig. 63 is shown the distribution of the component currents.

Thus $C_1 = \sqrt{(240)^2 + (174)^2} = 296$ amps.
                $C_2 = \sqrt{170^2 + 104^2} = 199$,,
                $C_3 = \sqrt{90^2 + 44^2} = 100$,,

The power factors are as follows :—

For C_1 cos $\alpha_1 = 1 \Big/ \sqrt{\Big\{1 + \Big(\frac{174}{240}\Big)^2\Big\}} = 0.81$;

For C_2 cos $\alpha_2 = 1 \Big/ \sqrt{\Big\{1 + \Big(\frac{104}{170}\Big)^2\Big\}} = 0.85$;

For C_3 cos $\alpha_3 = 1 \Big/ \sqrt{\Big\{1 + \Big(\frac{44}{90}\Big)^2\Big\}} = 0.9.$

The size of the conductor s, in a non-inductive main, can be found, if we have to design (1) for a given drop v, since

$$v = C_1 r_1 \cos \alpha_1 + C_2 r_2 \cos \alpha_2 + C_3 r_3 \cos \alpha_3$$

$$= C_1 \frac{L_1}{Ks} \cos \alpha_1 + C_2 \frac{L_2}{Ks} \cos \alpha_2 + C_3 \frac{L_3}{Ks} \cos \alpha_3,$$

or (2) for a given power loss, w, since

$$w = C_1^2 r_1 + C_2^2 r^2 + C_3^2 r_3$$

$$= C_1^2 \frac{L_1}{Ks} + C_2^2 \frac{L_2}{Ks} + C_3^2 \frac{L_3}{Ks}.$$

Calculations of this kind, if attempted for a complete network, would become extremely laborious. It is generally
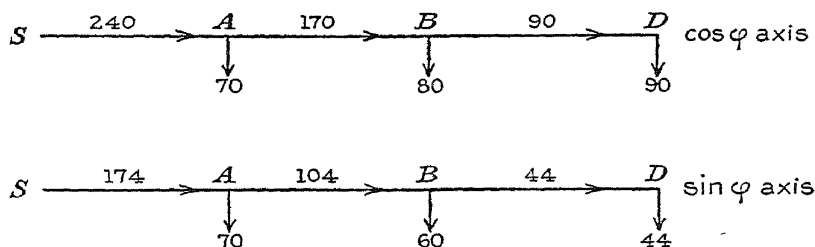
Fig 63

a sufficient approximation to calculate for non-inductive conditions and then apply a correction for the average power factor.

When supplying several sub-stations from an E.H.T. trunk main, the capital cost of which is heavy, it would certainly be worth while to carry out accurately the analysis we have indicated above.

Note.—The example of the two parallel circuits given on page 132 can be worked out by the above method, but the algebra is very cumbersome. The two cos φ values are

$$C_1' = C_1 \frac{R_1}{Z_1} \quad \text{and} \quad C_2' = C_2 \frac{R_2}{Z_2};$$

and the two sin φ values are

$$C_1'' = C_1 \frac{L_1}{Z_1} \quad \text{and} \quad C_2'' = C_2 \frac{L_2}{Z_2}.$$

If these pairs are added respectively they become $\Sigma C_1'$ and $\Sigma C_1''$. Then add the squares of these and take the square root, and we arrive at the same result for $C_1/(C_1 + C_2)$.

CHAPTER XI.

Mechanical Analogies.

The expressions " resonance " and " capacity effects " are popularly employed when dealing with all abnormal pressure rises, although resonance often plays but little part in their production. To the mains engineer their dangers are well known, and fortunately efficient safeguards are now available by which these dangers can be minimised.

To deal first with the question of resonance, properly so called, it may be stated that it is not, as a rule, the chief source of trouble on alternating circuits. It is, however, capable of explanation in an elementary way with greater clearness than some of the other kinds of pressure rises, and will, therefore, be first considered. Even in this case, the true physical meaning of the electrical phenomenon cannot be appreciated, unless the general principle of resonance has been studied, in relation to other forms of energy, such as mechanical vibrations and sound waves.

In mechanics the principle is exemplified with elastic bodies, which can be set into vibration, if they are subjected to rhythmic impulses at intervals which correspond with the natural period of vibration of the bodies themselves. A classical instance of this phenomenon in heavy engineering is the breaking of the propeller shafts on large steamships, where the changes of stress produced in the shaft by the unequal turning moment of the cranks may happen to follow each other at intervals which correspond to the natural period of torsional vibration of the shaft itself. An ample diameter of the shaft will not necessarily annul the effect; the proper remedy is so to choose its diameter that there is no longer synchronism between its natural period of torsional vibration and the

number of revolutions of the engine. Breakages of crank shafts, due to similar causes, were at one time not uncommon with certain types of central station engines.

In the case of the propeller shaft the amplitude of the effect is very small, but it is the synchronous recurrence of the maximum stress which causes the breakage.

A suspension bridge is another instance where mechanical resonance may be a source of danger. The bridge has a natural period of oscillation, and if a varying load be applied to it (such as that of a company of soldiers marching in regular time) the amplitude of swing may be so augmented if the swing produced by the marching is synchronous that the bridge will give way. The collapse of the suspension bridge at Angers in 1850, killing 226 soldiers, is a historic example of this kind of resonance.

A similar problem has to be considered by the shipbuilder in providing sufficient stability against rolling for the worst conditions, these occurring when the period of the waves is equal to the period of rolling of the ship in still water.

Although, theoretically, the smallest synchronous stresses would produce very large effects in many mechanical structures, the danger is lessened in practice by the stiffness of the materials and the presence of friction. Similarly, in electric circuits a moderate amount of resistance will lessen the enormous increase in pressure and current which are theoretically possible.

In acoustics, from which the term resonance is derived, the phenomenon is well known. The standard experiment is to make a vibrating tuning fork communicate its movement, by means of a sounding board or through the air, to another tuning fork which has the same pitch or vibrational period. Here, however, there is no multiplication of the amplitude by the receiving fork. The suspension bridge analogy probably illustrates most closely what happens in a resonating electric circuit.

Pressure Rises due to Resonance.

From what precedes it will be clear that the necessary condition for any kind of resonance is the application of artificial or forced vibration to a body, which is capable of vibrating naturally,

In an electric alternating circuit the waves of E.M.F. and current produced by the generator are obviously of the nature of forced vibrations. Now, what are the natural vibrations ? These are produced by the discharge of a condenser or a circuit containing capacity, under certain conditions as to the amount of inductance and resistance associated with it. A concentric or multi-core cable system acts, of course, as a condenser, and *if the resistance is small*, as it usually is, this condenser will have an oscillating discharge, with a natural period depending only on its own capacity and the inductance in circuit.

The algebraic relationship is

$$2\pi n = \frac{1}{\sqrt{LK}}, \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (1)$$

where n is the frequency of the natural oscillation, L, the inductance and K the capacity in series with it. If we take the general equation for a circuit containing capacity, inductance and resistance, and assume the resistance term small enough to be neglected, we get the simplified form

$$\frac{d^2Q}{dt^2} + \frac{Q}{LK} = 0. \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (2)$$

It is well known that this is the equation for the regular vibrating motion called Simple Harmonic, in which the magnitudes of the displacement follow those of the curve of sines. Consequently the correct solution is to give Q the value $Q = A \sin pt$, or $A \cos pt$, where A is a constant, and $p = 2\pi n$, n being the frequency. Take $Q = A \cos pt$, then

$$\frac{dQ}{dt} = -Ap \sin pt, \text{ and } \frac{d^2Q}{dt^2} = -Ap^2 \cos pt = -p^2 Q.$$

Substitute in (2) and it becomes

$$-p^2 Q + \frac{Q}{LK} = 0, \text{ or } p^2 = 1/LK,$$

or, as above, $2\pi n = 1/\sqrt{LK}$.

The time t required for a complete vibration is such that $n = 1/t$.

We can arrive at the time t from another consideration. If an impulse is given to a body capable of S.H. vibration, for

example, at the middle point of a stretched string a wave form
will be propagated along the string with a speed v, so that if l
is the length of the string to the fixed point of support or node,
$l=vt$, where t is the time occupied in the propagation.

The maximum amplitude obviously occurs at the place
where the impulse is applied, and reckoning from that point
to the node we have one quarter of a period or wave form.
Taking the curve of sines as an example, it is the portion of the
curve representing the values of the sine between $\pi/2$ (maxi-
mum value) and 0 (minimum value). Thus, the time of a
complete vibration is $t=4l/v$, or $n=v/4l$, if we apply the
analogy to an electric line of length l, subjected to natural
vibrations only. The speed of propagation v of an electric dis-
turbance or wave, is theoretically the speed of light, 186,000
miles per second, but the effect of surrounding bodies and other
causes bring the actual speed considerably below this figure.

Now, since $2\pi n=1/\sqrt{LK}$, or $n=1/2\pi\sqrt{LK}$, it follows that
the quantity LK is a natural constant, and, broadly speaking,
it is the same for every line of the same length, apart from dis-
turbing factors. This is clear from the equivalent form for
$n=v/4l$, whose variation depends only on the length of the
line.

It is impossible to explain all the aspects of this phenomenon
in this short and incomplete sketch, but we wish to emphasise
that every line, which has capacity and inductance in itself
or associated with it, has a pecfectly definite natural frequency
n. Mr. J. S. Peck, in his Paper (" Proc." I.E.E., June, 1908)
gave an example of the determination of n by observing L and
K for an actual transmission line.

In that example, L was 0·075 henrys, and K was $0·16 \times 10^{-6}$
farads. Hence, $n=1/2\pi\sqrt{LK}$

$$=1/2\pi\sqrt{0·075 \times 0·16 \times 10^{-6}}=1,600 \text{ periods per second.}$$

The length of the line was 20 miles, and in the discussion of
the Paper, Dr. A. Russell showed that the formula $n=v/4l$
gave $n=186,000/4 \times 20=2,325$ periods per second.

Actually v was less than the theoretical value 186,000, being
128,000 miles per second and, taking this figure, $n=1,600$
periods per second as above.

Before leaving this aspect of the subject we would observe that the speed of propagation of a forced vibration from an alternator is also approximately equal to the speed of light. Its forced frequency is much smaller than the figure found above (1,600), being of the order of 50 per second, which means, in other words, that the interval of time at any point between the passage of the maximum value of a forced wave, and that of the next succeeding one is one-fiftieth of a second.

A word as to the physical reason why $\sqrt{LK}$ is a natural constant may tend to clearness. On an overhead line, for example, the further the conductors are spaced apart the greater the inductance L and the less the capacity K. Conversely the opposite is true if they are close together as in an underground cable, so that $\sqrt{LK}$ is a constant quantity.

Returning now to an alternating circuit under a pressure E, we know that the current C is

$$C = \frac{E}{\sqrt{R^2 + \left(2\pi nL - \dfrac{1}{2\pi nK}\right)^2}},$$

from which it is seen that, when

$$2\pi nL = \frac{1}{2\pi nK}, \quad \cdots \cdots \quad (3)$$

the value of the current is $C = \dfrac{E}{R}$, which is the ordinary expression for non inductive conditions. Further, equation (3) is identical with equation (1), which was characteristic of the natural vibrations. Thus, if the inductance and capacity in series have values such as to neutralise each other, and to make $C = \dfrac{E}{R}$ and $\left(2\pi nL - \dfrac{1}{2\pi nK}\right)^2 = 0$, the necessary conditions for resonance are fulfilled. In other words, the forced vibrations, due to the generator E.M.F. and current, synchronise with the natural vibrations of the circuit, and will therefore augment the value of the pressure across the terminals of the condenser

and the current in the inductive part of the circuit. In Fig. 64 the voltage E_c across the condenser terminals AB will be

$$E_c = E \cdot \frac{\dfrac{1}{2\pi n K}}{R} = E \cdot \frac{1}{2\pi n K R}$$

instead of
$$E_c = E \cdot \frac{1}{\sqrt{1 + 4\pi^2 n^2 K^2 R^2}},$$

which is the usual expression for a circuit with resistance R and capacity K. If K has a fixed value and R is reduced the ratio of E_c/E will be correspondingly greater. The net result, when capacity and inductance in series neutralise each other, so as to produce resonance, is to cause the pressure at the condenser terminals to be very much greater than the supply pressure.
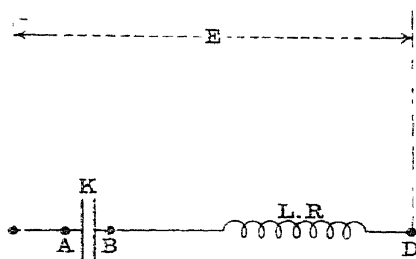
FIG. 64.

Fortunately in most high-tension lines this condition does not prevail, and the pressure rise due to resonance does not reach an infinite value, which it might do, if R were infinitely small. Another reason why resonance effects are the exception is that the value of n found from the equation $2\pi n = \dfrac{1}{\sqrt{LK}}$, for the usual lengths of line, or values of L and K is so high—*i.e.*, of the order 300 to 2,000 periods per second. As alternating-current supply is now mostly given at a frequency from 25 to 50, resonance with the fundamental waves of the generator is practically impossible. But the alternator may not produce waves of exact sine form, as has been assumed in the explanation given above, and the actual waves may contain harmonics or overtones.

L 2

These harmonics are little ripples on the fundamental wave, and, although of small amplitude, their frequency may be 3, 7, 13, or any odd multiple of times greater than that of the fundamental, and hence one of them may have a value which satisfies the conditions of resonance. The amplitude of an upper harmonic (or the energy it possesses) is so slight that resonance with it does not generally produce a dangerous pressure rise.

Even when *exact* synchronism does not exist between the fundamental waves (or one of the harmonics) and the natural waves, resonance may still occur to a greater or less extent, depending on the nearness with which these two values approximate to synchronism. Frahm's frequency indicator illustrates this, as there are always some reeds near the one in actual synchronism, which vibrate with the same applied frequency, but to a much less extent.

The effect of load currents is to diminish the maximum values to which the voltage and current will attain under resonating conditions. This is not perhaps of great assistance to those who have to watch for possible breakdowns in the mains, as there will frequently be times of light load on certain circuits, which would offer favourable conditions for abnormal pressure rises. On A.C. systems it is possible to have a number of combinations of the cables and transformers, so that if certain switching operations are carried out, the inductance of the transformers and the capacity of the mains may be put in series and this will produce resonance.

It must not be forgotten that, although $\sqrt{LK}$ gives a high value for the natural frequency when L and K refer only to the line itself, we can have very different values of L and K for the apparatus in circuit, and the natural frequency may be low enough to cause resonance even with the fundamental frequency of supply.

Prevention of Resonance.

The safeguards to prevent injurious pressure rises of the kind described are briefly as follows. Most of them belong more to the generating department, and are out of the control of the distribution staff.

1. Employment of an alternator which gives practically pure sine waves and few or no harmonics.

2. Permanently earthing the outer at one or more places through a non-inductive resistance. This should be of such an amount, that the rush of current through it is just sufficient to blow the fuses or trip the circuit-breakers on the inner, when a resonance rise occurs.

3. When connecting an uncharged main to a separate generator, run up the latter to the speed of normal frequency before exciting the fields, and then regulate the exciting current until the normal pressure is gradually attained. This avoids the possibility of resonance with frequencies (or harmonics of them) less than the normal, through which the generator voltage passes in running up. Alternators should never have their speeds run up or down, when excited, for fear of passing through a resonating value. For the same reason a long feeder for a motor or converter should not be switched off at the station end while the machine is running; in slowing down it may pass through a resonating value of the frequency.

The best practical way of investigating the possibilities of the occurrence of resonance in any circuit is not to calculate the values of L and K, but to make use of the Duddell oscill-ograph, which will indicate for any conditions under which the mains are tested whether resonance is present in any degree, or whether it is likely to occur with any modification of the conditions.*

Pressure Rises produced on Closing a Circuit containing Capacity and Inductance.

These phenomena are often loosely ascribed to reson ance, which is misleading. To make use of a mechanical analogy, they are closely akin to the impact of a load on an elastic body, as they are due to the sudden application of a voltage, E, to a circuit capable of natural electrical vibration. When a weight, *w* (Fig. 65), is applied gradually to the spiral spring suspended at P, it will produce an elongation equal to

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* A mathematical study of resonance, but with many practical points of view, is to be found in Mr. M. B. Field's Paper, " Journal " Inst E.E., June, 1903, Vol. XXXII. (*See* also ELECTRICIAN, Vol. L., p. 979).

FA. The tension of the spring, equal to w, can then be represented by the ordinate AK, and at any other point, L, during the process of stretching the tension is given by LM. If now the weight w be *suddenly* applied its potential energy, as it falls, will be diminished proportional to $w \times$ FA at the point A, and this change of potential energy is represented by the rectangle AKEF.

From Hooke's law the work done in stretching the spring a distance of FA is represented by the triangle AFK. There is thus a balance of the potential energy represented by FEK, which appears as kinetic energy, and if v be the velocity of the weight at the point A, this kinetic part will be $\frac{1}{2} \cdot wv^2/g$.
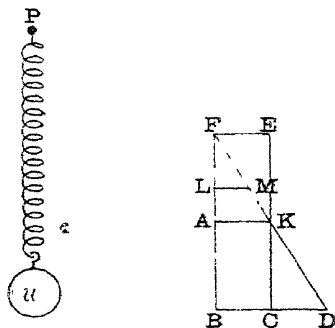
FIG 65.

The weight will then continue moving, but with gradually diminishing speed until it reaches B. At this point all the kinetic energy it possessed at A will have disappeared as part of the total work done in stretching the spring from A to B.

The fall of the weight from A to B is equivalent to a diminution of its potential energy of $w \times$ AB, represented by the rectangle AKCB. This is one part of the work done in stretching the spring, and the balance of the work done, shown by the triangle KCD$=$FEK, is supplied by the kinetic energy which the weight had stored up in it at A.

It will be seen from the diagram that the ordinate, which gives the tension of the spring at any point, is BD at B, and is equal to twice AK, which represented the normal tension due to a weight steadily hanging on the spring, and thus it can be

stated generally that the tension produced by an impact or suddenly applied load is twice that due to a steady load. After the original impulse, and movement of the weight to B, it will continue to vibrate up and down from A until the frictional resistance of the air and of the spring itself bring it to rest at A.

In order to study the close resemblance which this mechanical example bears to the effect produced in a condenser when suddenly connected to a supply at constant potential, it is best to write down the equation representing the state of things when the weight in its fall has reached the point A. The law of conservation of energy gives at once the following relationship —

Loss of potential energy at A=work done+kinetic energy. Or, if FA=x,

$$wx = \tfrac{1}{2}Tx + \frac{\tfrac{1}{2}wv^2}{g} \quad . \qquad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

As A is the normal position, when the weight is gradually applied T=w, and it follows that the kinetic energy, when the weight is travelling past that point, is equal to the work already done. At B the velocity v=0, and, therefore, T=$2w$. The corresponding terms in the electrical analogue—*i.e.*, a circuit containing capacity and inductance suddenly connected to a source of constant E.M.F., are as follows —

Weight, w corresponds to voltage of supply, E.

Tension, T corresponds to voltage on condenser plates, V.

Displacement, x corresponds to quantity of electricity, Q.

Velocity, v ($=dx/dt$) corresponds to current$=dQ/dt=$C.

Mass, w/g corresponds to inductance, L.

On application of the E.M.F., E, after a very small interval of time (so small that E may be supposed constant throughout, whatever its law of variation), the condenser will be charged to a pressure V, so that

$$EQ = \tfrac{1}{2}VQ + \tfrac{1}{2}LC^2 \quad . \quad . \quad . \quad . \quad . \quad (2)$$

by transposition of the mechanical terms in the equation (1).

At this stage of charging, the " potential or electrostatic energy " part is equal to the " kinetic or electromagnetic energy " part, and V=E, but the charging current C, then at its maximum, cannot stop suddenly, and only dies down to zero

when the pressure V across the condenser is equal to twice the supply pressure E. This can be seen from equation (2), for, when C=0, V=2E.

In stating this possible maximum the resistance of the circuit has been neglected so that, in practice, a less surge of pressure than 2E is to be expected.

The rise will also be less than twice the maximum voltage when an alternating current is employed, if the phase of the voltage, at the instant of switching on, is not passing through its maximum value. On the other hand, as Mr. Duddell points out, if the sudden switching on is imperfect and several contacts follow each other, we may get a greater rise than 2E. For instance, if after the first contact the cable is left charged to potential $+e$ and then contact is made again at the middle of the following half period when the voltage is $-e$, the change of voltage applied to the condenser is $E+e$, and the first swing may amount to $2(E+e)$, or the voltage rise measured from the zero line $2(E+e)-e=2E+e$. In the worst case of $e=E$ the maximum rise is 3E. For a sine wave this is $3\sqrt{2}$ or 4·2 times the R.M.S. value of the voltage.

Just as the weight vibrates on the spring so will the pressure in the condenser oscillate between zero and the high value, until it ultimately reaches the normal value. These oscillations of pressure are very rapid, and have the *natural* frequency of the circuit.

This can be proved by reference to equation (2). At the mean position $\frac{1}{2}QV=\frac{1}{2}LC^2$, or electrostatic=electromagnetic energy, but since $Q=KV$, where K is the capacity in farads,

$$\tfrac{1}{2}KV^2=\tfrac{1}{2}LC^2,$$

or
$$C=V\sqrt{\frac{K}{L}}=KV\sqrt{\frac{1}{KL}}. \quad \ldots \ldots (1)$$

But the current C in a condenser of capacity K in a circuit whose frequency is n is

$$C=KV2\pi n. \quad \ldots \ldots \ldots (2)$$

Thus, to satisfy (1) and (2) it is necessary that $2\pi n=\sqrt{\dfrac{1}{KL}}$ which has already been shown to be true of the natural frequency n.

To avoid injurious pressure rises of the type just described when switching cables into circuit, certain precautions have to be taken. To begin with cables for voltages up to 3,300, we may say at once that their factor of safety is so high that no special methods need be adopted. For E.H.T. cables to be worked with a delta system oscillograph experiments have shown rises of 4·5 times the R.M.S. value, when the cables were switched on with the distant ends open. Conversely, when these were connected to a transformer the pressure rise was only 20 per cent. above the normal.

Thus, with E.H.T. delta systems the cable or line should have its distant ends *closed* before switching on For a star system with neutral point earthed and distant ends open the rise does not exceed twice the normal pressure, and this momentary effect will not damage the cable when switched on. Th s operation on star systems, therefore, should be done with the ends of the cables open.

As will be gathered from the description of these switching on effects, no harm can ensue when switching off a cable, if the switch breaks the circuit definitely without a sequence of partial contacts   The recommendations given above are due to the British Insulated & Helsby Cable Co , and are based on their extensive experience with E.H.T. cables made to British standards.

Pressure Rises on Switching off Heavy Currents.

These are frequently spoken of as being due to resonance, but although oscillations are produced when a heavy current is broken, there can be no resonance as the original forced vibration has ceased with the breaking of the current.

The mechanical analogy is not quite so simple in this case. Returning to the spiral spring and weight, suppose the latter to have a forced simple harmonic vibratory movement. so that it was doing work against an external force conforming also to the S H law   If this force be withdrawn, when the speed is a maximum—that is, when the weight is passing through its mean position—the kinetic energy it possesses must find an outlet in stretching the spring. The amount of stretching will depend on the mass and the speed. If T is the final tension in the spring, when the mass comes to rest after a displacement,

.x. the work done, $\frac{1}{2}Tx$, must equal the kinetic energy stored up in the moving mass $\frac{1}{2}mv^2$. To utilise the energy equation $\frac{1}{2}Tx=\frac{1}{2}mv^2$ for an electric circuit, consider a large alternating current C, with a frequency n, passing through a circuit containing an inductance, L, and a capacity, K, and a resistance small enough to be neglected as a first approximation. An interruption of the current C corresponds to the withdrawal of the external force in the mechanical analogy, and should the phasal value of the current happen to be at its maximum the electro-kinetic or electromagnetic energy it possesses may be very large, as it is proportional to the instantaneous value of C^2. Thus, the electromagnetic energy equal to $\frac{1}{2}LC^2$ has no outlet except in charging the condenser of capacity K, formed by the cable conductors and their sheathings.

The condenser will finally be charged to a potential V, when all the electromagnetic energy is converted into the electrostatic or " potential " form. Its value corresponding to $\frac{1}{2}Tx$ above will be $\frac{1}{2}QV$ (and since $Q=KV)=\frac{1}{2}KV^2$. The amounts of these two alternative forms of energy must be equal—*i.e.*, $\frac{1}{2}KV^2=\frac{1}{2}LC^2$, and they will oscillate from one form to the other with a frequency which is the *natural* frequency of the circuit.

It will now be clear that the phenomenon cannot be one of resonance, as the forced oscillations cease entirely when the circuit is broken.

A happy analogy of the effect produced by the stoppage of a large alternating current is that of striking a blow on a tuning fork. A large proportion of the work done by the blow will appear as vibrations of the tuning fork, which, of course, will have their natural period. In contrast with this is the resonance phenomenon of the sympathetic vibration of two tuning-forks of the same pitch when only one of them has been set into vibration.

The relation $\frac{1}{2}KV^2=\frac{1}{2}LC^2$ is different from that found for the case of closing a circuit, inasmuch as C is now the independent variable—that is, it may have a wide range of values depending on the external energy it had been furnishing. Whatever value C may have,

$$V^2=C^2 \cdot \frac{L}{K} \text{ or } V=C\sqrt{\frac{L}{K}},$$

and thus V, the *additional* rise in pressure on breaking the current C, will be proportional to its value, and will depend also on the electric constants of the line. As already shown, when $\frac{1}{2}KV^2 = \frac{1}{2}LC^2$ is the condition characteristic of the circuit,

$$C = KV\sqrt{\frac{1}{KL}} = KV2\pi n,$$

or $2\pi n = \sqrt{1/KL}$—that is to say, n is the frequency of the natural oscillations of the line. These oscillations are quickly damped down by the losses due to resistance, hysteresis and eddy currents. Pressure rises of the kind described, being directly proportional to the current broken, may reach dangerous values when the current is very heavy, such as that produced by a short-circuit. It will also be recognised from the expression $V = C\sqrt{L/K}$ that the pressure rise will be accentuated the more the inductance and the less the capacity in the circuit. High inductance means greater electromagnetic energy, and small capacity means a high voltage when the electrostatic energy $\frac{1}{2}KV$ becomes equal to the electromagnetic. In underground systems with high capacity the dangers from this kind of pressure rise are less than on overhead lines, with small capacity and a good deal of inductance. The safeguard in breaking ordinary load currents lies in the use of oil break switches, which have the property of interrupting the circuit at or near the moment when the current is zero, or when the energy is entirely in the electrostatic form. A condenser connected across a switch or fuse will tend to break the arc immediately, because the condenser behaves, until charged, as a momentary short-circuit to the arc ; lead-covered cables may act as condensers in this way. On some of the long transmission lines in America it is found to be easier to work with high voltages than with those relatively lower, because, the current being less with the higher pressure, the effect of breaking the circuit is not so disastrous.

Lightning Arresters and Pressure Dischargers.

To guard against the effects of a short-circuit is not such an easy matter, as a pressure surge is bound to occur. In order to prevent the high pressure due to this or to resonance

from damaging the insulation between the inner and the earthed conductor, possibly at a number of points, some form of lightning arrester has to be employed.

There are many varieties of this apparatus, but for underground systems practically the intermittently arcing type alone is used.

The general construction is to have some form of spark gap (either single, as in the Siemens horn type, or multiple, as in the Wurtz type), one terminal of which is connected to the H.T. conductor and the other to earth.

The difficulties in the adjustment and operation of lightning arresters, which should discharge with certainty a moderate rise of pressure above the normal, are considerable. The Land und See Kabelwerke have a very neat arrangement of an adjustable relay spark-gap, with a high resistance in series, which brings the main spark-gap into play as soon as the resistance of the air has been broken down by the ionization produced by the preliminary shunted discharge.

It is also necessary to limit the rush of current when an arrester operates, and for this purpose a high resistance must be placed in series with the earthed terminal.

A very convenient design of resistance of this kind has been devised by Mr. H. Brazil, of the Charing Cross, West-End & City Co., which takes the form of granules of carbon lying in deep grooves in a fire-clay block. The superiority of this form as compared with those consisting of carbon rods or liquids has been fully proved by experiment.

The value of the resistance can be easily varied to suit the system, and it remains constant after repeated discharges. It can absorb large amounts of power for several minutes, and being made of fire-proof material it is indestructible by heat. Resistances of this kind can also be used for earthing the outers of concentric cables at the station, so that when an earth occurs the current need never attain higher values than those sufficient to trip the automatic cut-out on the faulty main.

A useful adjunct to pressure discharging spark-gaps is the apparatus devised by Messrs. Brazil & Gooch for indicating to the switchboard attendant that the arrester has operated. The

apparatus consists of a small transformer, the primary of which is connected between the resistances and earth, or as a shunt across a small portion of the resistance, the earth end of the winding being also connected to the iron of the transformer. The current through the secondary of the transformer causes a shutter to fall and complete the circuit of an electric bell, which continues to ring until the shutter is replaced. Instead of the bell, a recording instrument can be used, which shows the exact time at which the discharge occurred. From the particulars filled in by the switchboard attendant of the machines switched off or on at the time and the number of cables in use much valuable information can be obtained as to the causes of pressure rises in the system. Bad paralleling, faulty insulators and transformers, &c., are detected, and, when a short occurs on a cable or machine, it shows how far the resulting excess pressure extends over the system. With a simple modification the apparatus can also be adapted to three-phase extra-high-tension systems with unearthed neutral.

Details of the different varieties of lightning arresters in use will be found in a Paper by J. S. Peck, "Proc." Inst E E., vol. XL., 1908, and in the discussion thereon. There is also much valuable information in the Paper and discussion by J. H. Rider on the L.C.C. tramways system, "Proc." Inst.E E , Vol. XLIII., 1909.

Effects of Potential Waves.

One of the earliest cases of pressure rise on A.C. systems was that observed on the original concentric Deptford mains, and called from its discoverer, the Ferranti effect.

This is due to the distributed inductance and capacity of an open-circuited cable causing resonance when switched on. The effect is manifested in the augmentation of the potential at the distant end. We may regard the phenomenon as the reflection there of the E.M.F. waves of the alternator. If we consider an E.M.F. wave propagated along the cable at the speed v we know it will be reflected from the far end, which is a node, and on its return to the alternator its amplitude will be increased should it happen to coincide with another wave from the alternator meanwhile reversed in direction.

From what we have said of the natural frequency of these reflected waves, we know from the formula $n = l/v$ that the line l would have to be very long to make this effect possible to the fullest extent with fundamental waves. But there is usually the presence of upper harmonics to contend with, and such resonating rises are then possible, as indeed has been known ever since the early days at Deptford. When a short-circuit is suddenly broken at any point in a long cable a high voltage wave starts from it, and travels towards each end of the cable, and if this is open the wave is reflected there. If the end is connected to a high self-induction this will tend to produce a sudden arresting of the wave motion, and the amplitude will be doubled, this being the converse of the effect produced by a sudden application of the voltage we have already studied.

In concluding this chapter brief reference may be made to still another form of high-pressure disturbance, which may manifest itself in distributing systems, not so much on the mains themselves as on apparatus with windings like transformers. This phenomenon occurs when a high pressure is switched on to any system, and does not, like the other surges already considered, depend so much on capacity and inductance. It is an electrostatic effect and may be considered as the propagation of a " wave front " of potential into the system when a high pressure is applied to it. The wave front has a very steep potential gradient, and when this enters a coil it may produce much greater differences of potential between neighbouring windings than would be the case in normal working, and may thus cause perforation of the insulation. Other sudden changes of pressure, such as short-circuits or earths, may produce these steep waves of potential and cause similar troubles. The remedy is either to insulate very heavily the initial windings exposed to the exceptional stress or to use an exterior choking coil, which will absorb the wave—*i.e.*, smooth down its potential gradient, and for this purpose the windings of the coil can be insulated heavily enough to withstand the high pressures produced. At the risk of apparent over-indulgence in the use of analogy (the helpfulness and weakness of which we fully recognise), we will quote some remarks of Prof. Thornton, in the discussion on Mr. J. S. Peck's Paper ("Proc." I.E.E., December, 1912), which throw

much light on this still obscure phenomenon : "What we really mean by a potential front is the increase of the electrical stress in the insulation as the wave front advances along the line, caused by the wave front encountering inductance. Suppose that a round shaft carried a flywheel, and that a twist was applied with infinite rapidity to the shaft circumference : it is easy to see that the stress in the outer layers would be very much greater at the moment of application, before the stress was equalised over the section, than when a steady stage was reached ; and the greater the inertia of the flywheel the greater the stress at the shaft circumference. Also, even if the applied twist alternated periodically, the circumferential stress in the shaft would never be so great as at the moment of instantaneous application, unless this coincided exactly with zero."

See Field, " Proc." Inst. E E , Vol. XXXII , 1903 ; and Peck. *ibid*, Vol. XL , 1908, for further information on the subject of Pressure Rises. Mr Duddell, in his Presidential Address, 1913, has given an admirable account of the whole subject, including many original facts derived from his special knowledge and experience We are indebted to this address for several new ideas, since this subject was dealt with in the earlier edition, and we have found the bibliography, given by Mr. Duddell, of great assistance.

CHAPTER XII.

E.H.T. AND H.T. SYSTEMS · SUPPLY IN BULK.

Preliminary Considerations.

The problems discussed hitherto have been chiefly concerned with the retail distribution of electricity, but in the supply of electrical power in bulk by means of high tension cables some important new principles are involved. We can only give a short sketch of these principles, which fall more within the province of the consulting engineer for the complete scheme, than in that of the distribution engineer.

In this connection we propose to take as an example the main features of the system of mains laid down by the North Metropolitan Electric Power Supply Co., which supplies a wide variety of industrial power users and urban authorities scattered over large areas. In the preliminary project of a power scheme of this kind the choice of the type of mains, system and pressure, may at first sight appear to be quite free, but actually they are kept within fairly narrow limits by the conditions now to be stated.

The decision between overhead wires or underground cables is soon made in a densely populated area, since no urban local authority would permit the former. In industrial or purely agricultural districts, or for trunks mains crossing hilly country, as in Scotland or Wales, the overhead system is just as obviously the one to be selected.

Choice of System.

The choice of system of supply is not easy. The first question that arises is whether it should be continuous or alternating—the former involving the use of sub-stations with rotary converters, and the latter offering the advantage in simplicity of the static transformer for lowering the transmission pressure to that of the secondary networks.

The several varieties of alternating current, single, two and three phase, next require consideration.

The criterion usually stated to be the most important with these different systems is the relative economy of copper in the simple feeders, but practically there may be other factors which outweigh that of minimum weight of copper.

In comparing the different systems certain assumptions must be made. In low-tension distributors the declared pressure (approximately 250 volts) and the maximum permissible drop were the controlling factors. Maximum dielectric stress did not enter the question. In power transmission on the other hand the voltage is not limited, but the controlling factors are equality in the amount of power transmitted, and the total losses. Further, with any working voltage selected, the maximum dielectric stress on the insulation of the cables should be the same with all the systems to ensure a just comparison.

Relative Weights of Copper in different Systems.

To begin with the *continuous-current system* in which the current is kept constant, the pressure V to furnish power P is such that $P = C.V$.

The copper loss is $2C^2 r = 2\dfrac{P^2}{V^2} \cdot r$, where r is the resistance of one of the two wires forming the transmission circuit. With continuous current the maximum dielectric stress is, of course, directly proportional to V.

With *single phase alternating*, $P = C.V_1$, where C is the effective or R.M.S. value of the current and V_1 the effective pressure.

The maximum instantaneous value of the pressure is $V = V_1\sqrt{2}$, while the copper loss is $2C^2 r_1 = 2\dfrac{P^2}{V_1^2} \cdot r_1 = 4\dfrac{P^2}{V^2} \cdot r_1$.

If this loss is to be equal to the value with direct current $2\dfrac{P^2}{V^2} \cdot r$, then $r_1 = \frac{1}{2}r$, and the alternating-current main must have twice the cross-section of that for direct current. The same relation holds good for *two-phase systems* with four wires. For the

two-phase system with common return wire the following calculation shows clearly the reason why this system is now never proposed for trunk lines.

The power transmitted, $P = 2C \cdot V_1$, where C is the current in either of the outers and V_1 the voltage between them and the common return. The greatest effective voltage in the system is between the two outers, $V_2 = \sqrt{2} \cdot V_1$. The maximum instantaneous value of this is $V = \sqrt{2} \cdot V_2 = 2V_1$, and thus the power transmitted, $P = 2CV_1 = CV$ as in the direct-current system.

The common wire carries a current $C_2 = C\sqrt{2}$, and it has a resistance r_2 when working at the same current density as in the outers $= \dfrac{r_1}{\sqrt{2}}$.

The total losses in the copper are therefore : In the outers $2C^2 r_1$, in the common wire $2C^2\dfrac{r_1}{\sqrt{2}}$, or altogether

$$2C^2 r_1 + \sqrt{2}C^2 r_1 = \frac{P^2}{V^2}(2 + \sqrt{2})r_1.$$

When this is equal to the loss for direct current,

$$\frac{P^2}{V^2}(2 + \sqrt{2})r_1 = 2\frac{P^2}{V^2} \cdot r,$$

and

$$r_1 = \frac{2}{2 + \sqrt{2}} \cdot r.$$

The volume of copper is proportional to

$$2 \cdot \frac{1}{r_1} + \frac{1}{r_2} = \left\{ \frac{2(2 + \sqrt{2})}{2} + \frac{\sqrt{2}(2 + \sqrt{2})}{2} \right\} \frac{1}{r}$$
$$= (2 + \sqrt{2} + \sqrt{2} + 1)\frac{1}{r} = 5 \cdot 8\frac{1}{r}.$$

For direct-current the volume of copper was proportional to 2 and therefore the ratio of the two volumes is $1 : 2 \cdot 9$.

In *three-phase* working, the power $P = \sqrt{3}CV_1$, where C is the effective current in any of the lines and V_1 is the voltage between them. The maximum instantaneous value of the voltage is $V = \sqrt{2} \cdot V_1$. Thus $P = \dfrac{\sqrt{3}}{\sqrt{2}} \cdot C \cdot V$ and $C = \dfrac{P}{V} \cdot \dfrac{\sqrt{2}}{\sqrt{3}}$.

The copper loss in the three wires is $3C^2 r_1 = \dfrac{2P^2}{V^2} \cdot r_1$, while the corresponding value for direct current is $2 \dfrac{P^2}{V^2} \cdot r$.

Thus $r_1 = r$, and, the relative volumes of copper being proportional to $\dfrac{3}{r}$ and $\dfrac{2}{r}$, it is apparent that the three-phase system requires 1·5 times more copper than direct current, two wire.

In practice the selection of one of the systems indicated is not dependent on the relative volumes of copper alone. For example, in the constant current series system, as developed by Thury, in spite of the state of perfection to which he has brought it, the capital costs of the generating station, plant and switchgear are considerably more than those for alternating current. On the other hand, for equal amounts of energy lost annually the cost with direct is less than that with alternating current, as the greater part of the latter occurs at peak load. The difficulties with commutators and insulation on the machines are serious with direct current, but against this there are fewer troubles arising from capacity and inductance in the mains.

It is thus impracticable to arrive at a positive conclusion in regard to either system, unless actual figures are tabulated for the capital costs of the generating station and the transmission lines and the respective losses in the latter. A quantitative investigation of this kind is given in the excellent Papers by J. S. Highfield, Proc. Inst. Elec. Eng., Vol. 38, June, 1907, *ibid.* May, 1913.

In comparing single with three-phase the choice is easier as the systems do not present radical dissimilarities. Three-phase switchgear and transformers are costlier than those for single phase, and the price of the three-core cables is greater than the two-core or concentric, for equal weights of copper, on account of the necessity for insulating three conductors instead

of two, and providing a larger lead sheath. These disadvantages may go far to nullify the saving of 25 per cent. in copper afforded by the three-phase system. Still more is this true should the working pressures be greater than 30,000 volts. Above this value single cables are probably desirable, and they can now be constructed to work safely under 50,000 volts R.M.S. pressure on each or with 100,000 volts single-phase line pressure. With this construction the cost of insulation and lead sheath would be much higher for the three conductors required in the three-phase system. (*See* Part II., Chap. VII., HIGH-TENSION CABLES.)

Choice of Working Pressure.

Assuming that a decision has been made regarding system, the question of working pressure must then be closely studied. The principle underlying the choice of pressure, like that of the general character of supply, is the attainment of minimum cost of the plant and its operation with a proper regard to safety in running.

If cost of copper alone is considered, as we have already seen, the value of the pressure should be made as high as possible, but when cost of operation is included in the problem a certain pressure will be found to be best, depending upon the length of the line and the power to be transmitted. The greater the load and the radius of distribution the higher should be the pressure.

Very high pressures give great economy in copper, but they necessitate an enhanced cost for insulating the cables, or overhead wires, and for the generators and switchgear.

It is therefore not advisable to decide upon an excessively high pressure without examining carefully whether a lower pressure would not give a more economical result when all costs are included.

One factor in the problem of immediate interest to mains engineers is the effect of the thickness of dielectric on the capital cost of the cables. The principle of the potential gradient in the dielectric, as developed by Jona and O'Gorman, indicates at once that for heavier cross-sections of conductor a less thickness of insulation is required than for conductors of smaller diameter, when the maximum dielectric stress is the same in both.

Owing to this effect there exists a certain cross-section for every pressure which will give minimum cost, and it is thus inadvisable to employ a smaller cross-section than this with the idea of saving money on the cable.*

The curves in Fig. 66, taken from a Paper by Dr. R. Apt in the *Elektrotechnische Zeitschrift*, 1908, No. 8, illustrate the relation between cross-section and the total cost of con-
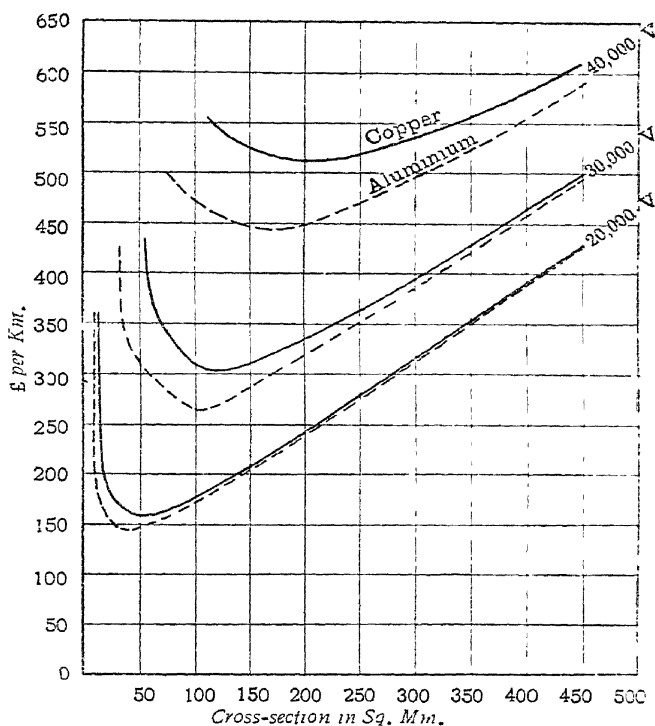

FIG. 66.

ductor (copper or aluminium) plus insulation. The values are comparative only, and not absolute, as the latter would depend on the actual dielectric strength of the insulation and the current prices of the raw materials.

In Fig. 84, Part II., Chap. I., the effect is illustrated in another and more striking fashion, the thickness of insulation

* This is the present accepted theory; as pointed out in Part II it does not altogether agree with practice.

required for a 500 mm. conductor being approximately only half that for 50 mm.

The relation between cost of copper and insulation is one of the important factors in arriving at the most economical pressure. The final choice must take into account the whole of the capital and running charges, for generating, switchgear and transmission plant.

Associated with the choice of pressure is the almost equally vital question of frequency, but this does not, *per se*, influence the design of the cable system and we cannot touch upon it here.

When the pressure is fixed upon, the current densities and cross-sections in the various lengths of line can be calculated from Kelvin's law. Care must be taken however not to make use of any cross-section smaller than the minimum indicated by the curves.

Particular attention must also be given to the question of heating with high-tension and extra-high-tension cables.

The thickness of the dielectric impedes the cooling of the copper to a much greater extent than with low-tension cables and the working current density must be correspondingly smaller. This factor must be remembered in calculating the total cost of cables, when comparing the effect of higher pressures.

Mr. J. R. Beard in a Paper * dealing with the three-phase systems on the North-East Coast has given much valuable and lucid information as to the detailed procedure for ascertaining the best voltage for a new project and for verifying the limits of economic distribution with an existing voltage.

In the short summary of his method, which we give, many of the principles referred to will be recognised as identical with those we have considered in earlier pages for the smaller low-voltage networks.

1. From the known data for generating costs the economic current density is first obtained. Since the energy losses in the cable at this current density are equal to the other annual charges it is possible to prepare curves showing the *total* annual charges per mile for any given value of the current. A set of curves corresponding to the standard voltages of 3,000, 6,000, 11,000 and 20,000, &c., are prepared in this way.

* Proc. Inst. E.E., No. 253, 1916.

2. The next step is to plot the data thus found in a more convenient form for discrimination as to the best voltage. The voltage which gives the lowest annual charges (or the economic voltage) for a given current per phase is determined by an examination of the curves in (1) and proceeding from that information, the average load in kilovolt-amperes per mile of main can be plotted against the economic voltage. When account is taken of the cost of switchgear per mile of main a set of curves is obtained in which the effect of this factor is included.

3. The next step is to lay out and calculate the system by assuming a voltage anticipated to be suitable to the district and its loading. From this the kilovolt-amperes per mile can be determined, and if this is compared with the curve connecting the load per mile and the economic voltage it can be recognised whether it is correct or whether the process will have to be repeated by assuming a different voltage.

4. Finally, the voltage drop in the system must be calculated to see that it does not exceed the permissible value for good regulation, viz., about 10 per cent.

As we have seen from the formulæ for pressure drop in inductive mains the power factor of the load and mains has an important bearing on the drop.

Lay-out and Regulation of High-tension Systems.

When alternating systems of 2,000-3,000 volts were originally laid down for lighting purposes, it was usually assumed, that, for the conditions anticipated, they would be self-regulating. They were mostly designed on the principle of the ring main, *i.e.*, with all the sub-stations connected to a pair of elastic conductors fed in two directions from the central station. When the areas dealt with were above a certain size and the loads increased due to demands for power, &c., it was found that a 2,000 volt system was not elastic enough without extraneous means of regulation. The ring main had the merit of giving a duplicate feed to each sub-station, with good security against stoppage of supply in the event of a fault, but

the pressure could not be varied at the different sub-stations except by adding a few extra turns to the transformer and thus adjusting the relative pressures once for all.

Where the area of supply is extensive with a ring main and when the load grows to unexpected amounts in certain districts it is necessary to adopt partially the separate feeder system with 2,000 volts just as with low tension.

Regulation of the pressure is done on each feeder by means of transformer boosters or induction regulators. Pilot wires are not necessary on the high-tension feeders, but a scale of boosting pressures can be calculated from the known resistance of the feeders, and the adjustment of the regulators is varied in accordance with the readings of the ammeters, the drop in voltage being directly proportional to the latter.

If the central station is situated very eccentrically to the main supply points it may pay (just as with low tension) to transmit the whole power by trunk feeders to a main sub-station, from which the subsidiary feeders can radiate.
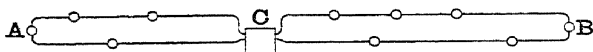
FIG. 67.

The regulation from a feeding centre of this kind is also much simpler.

Where duplication of the feeding cables is advisable, but the shape of the district is unsuitable for a ring main linking up the sub-stations, the arrangement shown in Fig. 67 may be adopted.

The concentric cable joining the central point of supply at C to A or B is laid in duplicate, and if a fault occurs between any of the sub-stations a supply can still be provided to all. The method is quite economical as the cross-section of copper in the looped main is a good deal less than with a single feeder supplying all the sub-stations

This is one of the most elementary forms of an inter-connected system. Mr. J. R. Beard gives many interesting diagrams of inter-connected extra-high-tension networks (*see* Proc. I.E.E., No. 253, 1916), and indicates the best geometrical relations of the sub-stations for different conditions.

The advantages of inter-connection, *versus* simple radiating feeders, can be succinctly stated as follows .—

1. Duplicate supply to each sub-station and greater security.

2. Fewer spare feeders and a better utilisation of the copper. (*See* the remarks in previous pages on Trunk and Bunched Feeders.)

3. The greater the area the better the results. This is akin to the problem discussed earlier of the best feeding frontier from any feeding point.

4. There is greater elasticity in the system for pressure regulation.

5. The lightly-loaded feeders help those heavily loaded, when they have a diversity factor.

Extra-High-Tension Mains (North Metropolitan System).

In extra-high-tension working over a large area like that of the North Metropolitan Co., London, little trouble is experienced with pressure drops to the main sub-stations at considerable distances from the power house. For example, at Barnet, which is nearly 10 miles by the cable route from Brimsdown, even assuming that the trunk feeders are working at maximum current density near the home end, the pressure drop would not exceed $4\frac{1}{2}$ per cent. Thus an extra-high-tension system of this kind is for all practical purposes self-regulating, and it is sufficient to raise the pressure a little over the whole area at night as the load comes on, and to reduce it gradually to its normal value in the early hours of the morning. This procedure keeps the actual pressure variations within 2 per cent. of the normal value.

Further references to the pressure regulating arrangements on the rest of the system are given below.

In the North Metropolitan undertaking the extra-high-tension transmission pressure is about 10,500 volts, three-phase. at a frequency of 50. An area of over 300 square miles in all is available for the company's operations, the southern section, with its trunk mains supplied by the power stations at Brimsdown and Willesden, being represented on the map, Fig. 68.

Particulars of the chief consumers, local authorities, traction and lighting companies, taking a supply in 1910, are

FIG. 68.

Scale of Yards

PARISH OF EDMONTON

PARISH OF WOOD GREEN

Main Sub-Station shown thus
Other Sub-Stations
H T Feeders
L.T Distributors
E H T Mains
Section Pillars
Network Boxes
Fuse Boxes
Sizes of Mains.

Dunhills Factory

WHITE HART LANE

CHURCH LANE MAIN SUB-STATION

LANSDOWN ROAD

Fuller Box Factory

BRUCE GROVE

DOWSETT AVENUE

CRAWLEY ROAD

Barber-Wilsons Works

BOUNDARY RD SUB-STATION

WESTBURY AVENUE

CHESTNUT ROAD

Eagle Pencil Factory

BROAD LANE

Duncan-Tuckers Works

Ice Factory

WEST GREEN ROAD

FOUNTAYNE RD. SUB-STATION

Clark's Iron Foundry Mills Equipment

BROAD LANE

SEVEN SISTERS RD. SUB-STATION

GREEN LANES SUB-STA

British Photo Mount Co

ST ANNS ROAD

North Eastern Hospital

SEVEN SISTERS ROAD

CROWLAND ROAD

indicated. In several instances (as at Barnet, Edmonton and Enfield) provisional orders for retail supply are being worked by the Company itself or by companies under associated control.

The Willesden District Council takes a supply from the Willesden power house at 3,000 volts to its central sub-station through 3,000 volt trunk feeders which are its own property. In parts of the area the 10,500-volt pressure is reduced to 3,000 volts for the secondary feeding network of high-tension cables supplying those districts in which a good demand for power is developing.

The Tottenham area is an instance of this kind, and the map in Fig. 69 shows the 3,000-volt ring main fed from the main sub-station in Church Lane, which is supplied at 10,500 volts. Several independent feeders are also shown running to some of the larger private consumers, and outlying sub-stations. It will be seen from the map that the furthest point of supply on the 3,000-volt ring main is about $2\frac{1}{2}$ miles from the main sub-station. The employment of an intermediate pressure between 10,500 and 415 volts thus offers considerable advantages. At 3,000 volts the whole of the district can be very effectively dealt with from the branch sub-stations, and the capital cost of these is much less than if they had been fed at 10,500 volts.

The ordinary public supply is three-phase with a four-wire system at a pressure of 415 volts between phases, or 240 volts between any phase wire and the neutral. In some districts, as at Barnet, Enfield and Stoke Newington, direct current is supplied to consumers, and at these sub-stations the pressure is regulated on the direct current side of the motor-generators or converters.

The present size (1918) of the company's system will be seen from the following figures : The length of the extra-high-tension main is 110 miles, high-tension 40 miles, and low-tension four-core 76 miles, with total connections amounting to 30,000 kw. The generating stations are situated, one at Brimsdown, the other at the opposite extremity of the southern area at Taylor's-lane, Willesden. Extra-high-tension current is generated at 10,000–11,000 volts in the former station, while at Willesden,

which originally had 3,000-volt plant, step-up transformers are used for supplying the trunk mains, but later generators are wound direct for 11,000 volts.

In the subdivision of the load between the generating stations a regular routine is adhered to unless there is trouble at one of the stations when the relative proportions can be arranged over the telephone. The actual adjustment is made by running the two stations in parallel for a short time, and then re-distributing the loads. The general procedure is to supply the sub-stations in the western section at Hendon (traction and lighting), Finchley and Barnet, Wood Green and Stoke Newington from Willesden, while Enfield, Tottenham and Ponder's End, in the eastern section, are run from Brimsdown.

Sub-Station Plant.

The 11,000-volt generators are star wound, but the neutral point is not earthed. There are three standard types of sub-station transformers : (1) 10,500 to 415 volts ; (2) 10,500 to 3,000 volts ; and (3) 3,000 to 415 volts. The first and third are delta wound on the primary side and star wound on the secondary, as this arrangement enables the earthed neutral to be connected to the middle point of the star, and also permits of dealing with an unbalanced load. The second type is star—star, partly for cheapness and convenience in taking off the tappings. The neutral point of the 3,000-volt star system is not earthed. All the main sub-stations are in buildings above ground, on sites which belong to the company. The large private consumers, taking power direct from the extra-high-tension or high-tension systems, furnish accommodation on their own premises for the necessary sub-stations, which, however, are under the sole control of the Company. One of the public supply sub-stations in Tottenham is underground and another is erected at Southgate for the general supply of the district, as it was found impossible to secure the necessary land for buildings above ground. Great care has been taken with the design of these underground sub-stations so as to render their operation safe and satisfactory. Transformer kiosks are not in general use, but they are occasionally used for

pioneer work in a new area, until a permanent brick sub-station can be built.

The close regulation of the pressure on the alternating light-ing systems, such as at Tottenham and Edmonton, is effected on the high-tension and on the low-tension sides by induction regulators, which may be cut out during the period of light load.

In the traction sub-stations practically no regulation is re-quired, although a certain amount can be effected by altering the exciting current of the direct current field magnets. There are no pressure regulators in the 3,000 to 415 volt *branch* sub-stations, as all the adjustments necessary on the 3,000-volt feeders are made at the main sub-station for a group of feeders or independent ring main system in a given district. Low-tension regulators are provided in those main sub-stations which transform down direct from 10,000 to 415 volts for pur-poses of public supply. In the power consumers' sub-stations, where the pressure is reduced directly to 415 volts there are no regulators. These are obviously unnecessary for two reasons : there is no extensive feeding system causing a drop in voltage, and, further, small variations of pressure when the supply is mainly for power are unimportant. Besides, the elasticity of the extra-high-tension system, as already pointed out, keeps the pressure fairly constant, *i.e.*, a little higher near the gene-rating station and a little lower further away. It is sufficient, therefore, to provide the transformers with tappings giving a $2\frac{1}{2}$ per cent. variation on the low-tension side, these tappings are decided once for all in accordance with the relative distances of the sub-stations from the power house.

Description of the Mains of the North Metropolitan Co.

The 10,500-volt trunk mains are 0 1, 0 15 and 0·2 sq. in. three-core from Willesden to Brimsdown throughout, with branches to Stoke Newington, Barnet, Enfield and Southgate. Smaller mains are used in the industrial area close to Brims-down, these consisting of a pair of 0·05 feeders to the Ediswan Works, and a ring main of 0·025 section, which supplies two other works in the neighbourhood. These cables are all paper-insulated and lead-covered, with a Board of Trade copper earth shield under the lead. They are mostly laid solid in earthen-

lead and possibly insulation, the expense of troughing, laying and street work generally remains nearly constant, and in London districts the latter items are unusually costly. Thus it pays to use smaller sections only where the distances are short and the road work easy.

This is not a question to be decided by Kelvin's law ; it depends inherently on the accurate forecast of the load, and whether it will pay better to lay the full-sized conductor in the first instance. If it be decided to lay sufficient copper only for a few years, this ought theoretically to be worked up to its economic current density before further copper is laid. With extra-high-tension cables, however, it will not be forgotten that the temperature rise may be of more importance than the restrictions of Kelvin's law.

End of Part I.

Part II.

PART II.

THE INSTALLATION AND MAINTENANCE OF CABLES AND CABLE SYSTEMS.

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CHAPTER I.
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THE CONSTRUCTION AND PROPERTIES OF CABLES.

Classification of Cables.

Cables for the transmission of electrical energy may be divided into three main groups, in accordance with the character of their insulation. They may have —

(A) Fibrous dielectric (paper or jute)
    (a) Protected by lead sheathing.
    (b) Protected by bitumen sheathing.
(B) Rubber dielectric.
(C) Vulcanised bitumen dielectric.

Any combination of these dielectrics may be used. Copper is the usual conductor, but aluminium may also be used.

The insulation of cables, besides being of high specific resistance, ought to be (i.) impervious to moisture, (ii.) flexible, (iii.) tough, (iv.) able to resist high temperatures, (v.) chemically inert, (vi.) capable of resisting high disruptive voltages, (vii.) homogeneous, (viii.) preferably non-inflammable.

In the (A) class, quality (i.) is obtained by using a waterproof sheathing, (ii.) by impregnating the dielectric with oil, (iii.) by using good paper. Class (B) is weak in qualities (i.) and (v.). Class (C) is weak in (iv.), (v.), (vi.), (viii.) and sometimes (vii.).

In what follows the expression *positive cable* means that conductor of a three-wire continuous-current system which is maintained *above* earth potential; by *negative cable* is meant that conductor which is maintained *below* earth potential.

Copper Wire Conductors.

For underground cables soft or annealed electrolytically refined copper is used. This copper comes to the manufacturer in the form of wire bars, weighing about 140 lb.

They are first heated in a furnace to a bright red heat, then broken down in rolls and afterwards rolled into rods. After being cleaned from oxide, by pickling in acid, the rods are drawn into wire through iron or diamond dies. The wire has now to be annealed, which is done by heating it in a retort to a temperature of from 800°F. to 1,100°F. In the " Bates & Peard " retort the wire is carried slowly through by means of an endless conveyor. The retort containing steam is water-sealed at both ends to prevent the entry of air. The copper wire emerges from the retort annealed, and as clean as when it went in, and is then ready for stranding into a cable.

The British standards for copper conductors at present (1917) in use were issued by the Engineering Standards Committee (No. 7, revised March, 1910). The International Electrotechnical Commission have, however, published (No. 28) rather different standards, which have been adopted by the American Institute of Electrical Engineers, and with which it is to be expected that the British Standards will be made to confirm at some future date.

The standards affecting underground conductors are given below. " E.S.C." signifies the Engineering Standards Committee, and " I.E.C." the International Electrotechnical Commission.

1. *E.S.C.*—A wire 1 metre long, weighing 1 gramme, and having a resistance of 0·1508 standard ohm at 60°F., is taken as the E.S.C. standard for annealed high conductivity commercial copper.

. *I.E.C.*—At a temperature of 68°F., the resistance of a wire of standard annealed copper 1 metre long, and of a uniform section of 1 sq. mm. is 0·0172414 ohm.

2. *E.S.C.*—Copper is taken as weighing 8·89 gms. per cubic centimetre at 60°F. (=555 lb. per cubic foot).

I.E.C.—At a temperature of 68°F. the density of standard annealed copper is 8·89 gms. per cubic centimetre.

3. *E.S.C.*—The average temperature coefficient of 0·00238 per degree F. (0·00428 per degree C.) is adopted for commercial purposes

I.E.C.—At a temperature of 68°F. the " constant mass " temperature coefficient of resistance of standard annealed copper, measured between two potential points rigidly fixed to the wire is 0·00218333 per degree F. (0·00393 per degree C.).

4. *E.S.C.*—Two per cent. variation from the adopted standards of resistance and weight are allowed in all conductors.

5. *E S.C.*—An allowance of 1 per cent. increased resistance as calculated from the diameter is allowed on all tinned copper conductors between diameters 0·118 in. and 0·028 in. inclusive.

6. *E.S.C.*—For the purpose of calculation, a lay, involving an increase of 2 per cent. in each wire, except the centre wire, for the total length of the cable, is taken as the standard.

We have met with a certain amount of misunderstanding in connection with the use of the temperature coefficient. The resistance and temperature are connected in this way,

$$R_t = R_{t_o}[1 + a(t - t_o)],$$

where R_t is the resistance at some temperature t R_{t_o} is the known resistance at a temperature t_o, and " a " is the temperature coefficient. Thus the I.E.C. standard wire has a resistance $= 0·01724$ ohm at 68°F. ; its resistance at 60°F. is then—

$$R_{60} = 0·01724[1 + 0·00218 \{60 - 68\}],$$
$$= 0·01724[1 + 0·00218 \{-8\}],$$
$$= 0·01724[1 - 0·01744],$$
$$= 0·01724[0·98256]$$
$$= 0·01694.$$

At any temperature greater than 68°, the quantity $(t - t_o)$ would, of course, be positive.

An easily remembered temperature coefficient is the approximate value 0·004 per degree C.

The coefficient of expansion of copper is 0·0000165 per degree C. ($= 0·0000093$ per degree F.)

Underground copper conductors are made up into cables each of a definite sectional area, which is (in Great Britain) generally some decimal fraction of a square inch. Thus.

common sizes for low tension distributors are 0·05, 0·1, 0·15, 0·2, and 0·25 sq. in , whilst feeders for low-tension work may have cross-sections up to 1·0 or 1·5 sq. in.

Any pocket-book or cable-maker's catalogue gives the resistances, diameters, &c., of standard sizes of cable. For completeness, the particulars of a few standard cables are given below :—

Stranded Circular Annealed Plain Copper Conductors.

Nominal area sq. in.	No. and size of conductors S.W.G.	Diameter of strand.	Weight. lbs. per 1,000 yds.	Resistance at 60° F. ohms per 1,000 yds.
. 0 022	7/16	0·192	265	1 086
0 034	19/18	0 240	405	0 7125
0 050	19 '0 058	0·290	591	0·4880
0·100	19/0·083	0·415	1,211	0·2383
0·200	37 '0 083	0·581	2,360	0·1224
0·250	37 '0 092	0 644	2,900	0·0997
0 50	61 '0 104	0 936	6,109	0 0473
1·00	91 '0 118	1·298	11,730	0 0246

Some of the above may be made up of different combinations of wires.

Three-core cables are made up to about 0·25 sq. in. section. The conductors may be either round or sector shaped, the object of the latter being to economise in insulation, lead and armouring. This saving is the more important the greater the proportion of the copper weight to the weight of the insulating material, or the lower the working voltage. In high-pressure cables the advantage of sector-shaped conductors is not very apparent. As regards the influence of sector shaped or round conductors, on the factor of safety of the cable at high voltages, the authors are of opinion that the shape of the conductors is of little or no importance.*

Low-tension concentric cables are made up to a sectional area of 0·5 sq. in., and high-tension concentric and triple concentric cables up to about 0·3 sq. in. Four-core cables for low-tension work are also listed up to 0·3 sq. in.

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* This view is not in agreement with the generally accepted theory.

Paper-insulated Lead-sheathed Cables.

This is the commonest form of cable for all classes of work.

Since paper is hygroscopic, the insulation resistance depends entirely on the protection afforded by the lead sheath. In a former edition of this book, the view was advanced that moisture might be prevented from penetrating into a *positive* cable by electric osmotic pressure. In the light of later experiments, we think this view is erroneous. Electric osmosis is a phenomenon dependent essentially on insulating capillary channels, or surfaces, and there would appear to be no such media in a well-impregnated paper cable. In half-impregnated cables, and cables containing very little oil between the layers of paper, some such action may take place. We have heard that some German manufacturers apply a continuous-current pressure to their cables after they have been immersed in water, in order to lower the insulation resistance, if there should be any defect in the lead. We think such a test is without any value, as from recent experiments we have made, we do not find that applying a continuous-current pressure to a cable with damaged lead immersed in water in any way hastens the lowering of the insulation resistance.

Paper Insulation.

Paper is made from " manila " fibre, straw, cotton, linen rags, jute, esparto grass, &c., and wood either chemically or mechanically treated Manila paper is always used by British makers because of its mechanical strength and resistance to rupture. It should be of a uniform texture, free from pin holes, and contain no trace of residual chemicals. There is an interesting Paper by Ll. B. Atkinson and C. J. Beaver which goes fully into the question of paper insulation.*

Messrs. Atkinson and Beaver state that pure manila paper only should be used. They go on to say :—

Samples of American and Continental cables have been examined in which chemical and mechanical wood papers were used entirely, and some German makers have gone so far as to maintain that chemical wood is preferable to manila. The chief disadvantages of

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* *See* THE ELECTRICIAN, Vol. LIV., pp. 702, 745, 784, 843.

the introduction of straw, grass or wood fibres in place of manila are as follows : —

(*a*) Lower dielectric strength and insulation resistance, and higher capacity.

(*b*) Deterioration in strength and elasticity of the paper when heated continuously or intermittently and consequent brittleness.

(*c*) Danger of rotting in course of time through the action of residual chemicals.

It is explained that manila paper is made with very little chemical treatment and without bleaching, and hence has not the disadvantage (*c*).

Paper consists essentially of cellulose ; wood consists of cellulose and ligneous material. In the preparation of " chemical wood " paper almost the whole of the ligneous part of the wood is eliminated by prolonged boiling in sulphite of lime, under pressure, and nearly pure cellulose is the result. Chemical wood fibres are readily recognised under the microscope by their riband-like appearance. Mechanical wood pulp is prepared by grinding logs of wood under hydraulic pressure against a revolving grindstone. The pulp produced still contains ligneous matter, and the fibres are all broken up. Hence paper made of this substance is wanting in mechanical strength and alters chemically when exposed to air and light. It would appear that this substance should be carefully excluded from cable paper. Manila fibres examined under the microscope appear as long smooth tubes. Esparto fibres are something like manila, but thinner and shorter, and the walls are thicker. To prepare paper for examination under the microscope the oil is dissolved out with benzol or. better, with acetone, and the paper well washed and boiled in a weak caustic alkali solution. It is now either shaken up vigorously with glass beads to break it up into its constituent fibres, or teased out with needles, and then mounted in glycerine. It can then be compared with labelled photographs of the different kinds of paper. The reproductions, printed with Messrs. Atkinson and Beaver's Paper referred to above, are excellent for this purpose. " Paper Technology," by R. W. Sindall, F.C.S., gives a good account of different kinds of paper, illustrated by micro-photographs. Paper used for telephone cables appears to be made of chemical wood or a mixture of chemical

wood and manila, the paper being classed commercially as " manila."*

Figs. 70, 71 and 74 are photographs of paper fibres from three English cables by different makers ; Fig. 73 is more highly magnified and is from the same cable as Fig. 71 ; Figs. 72 and 75 are from German cables, both by the same maker, but off different drums. The German paper is a mixture of chemical wood, manila, &c. All the English fibres are " manila."

A series of articles by Messrs. Clayton Beadle and Stevens beginning in THE ELECTRICIAN of April 16, 1909, should be referred to in this connection, also an article by Mr. Beaver in THE ELECTRICIAN of July 9, 1909. The following extracts are from these Papers :—

" Manila, properly speaking, refers to the *musa textilis,* a fibre very largely grown in the Philippine Islands . . . but such old ropes and their sources of supply do not consist only of manila, they include various aloe fibres, sisal, &c., and phormium tenax, a rope-making fibre from New Zealand."

" We wish to emphasise the fact that manila must be used in a generic sense to describe not only manila proper, but other fibres such as above mentioned. Furthermore, it is an anomaly to talk of manila hemp—manila is not hemp at all : hemp belongs to a very different class of fibres—hemp fibre is the *cannabis sativa.*"

" The leading authorities declare that they are often quite unable to distinguish flax from hemp under the microscope. This fibre, in its unbleached state, as well as the above fibres classed with manila, are found in manila papers as used for cables, and we think it would be quite fastidious of any cable manufacturers to reject the paper constituted of any of these fibres, including hemp proper, on the score that they are not real manila."

This last sentence is perhaps the explanation of an apparent anomaly Samples of paper from a cable were sent to a firm of chemists in London, experts in paper and to a botanist. The chemists reported about 70 per cent. of manila to be present, the botanist was only able to find one individual fibre which *might* be manila.
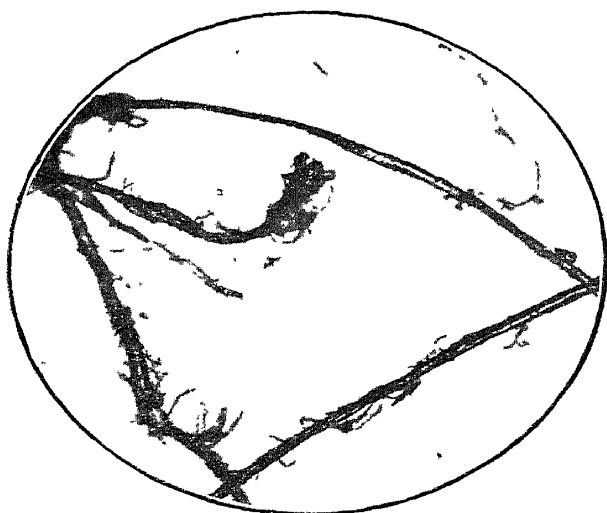
FIG 70.—PAPER FIBRES FROM ENGLISH CABLE.

Magnified 40 diameters (approximate)
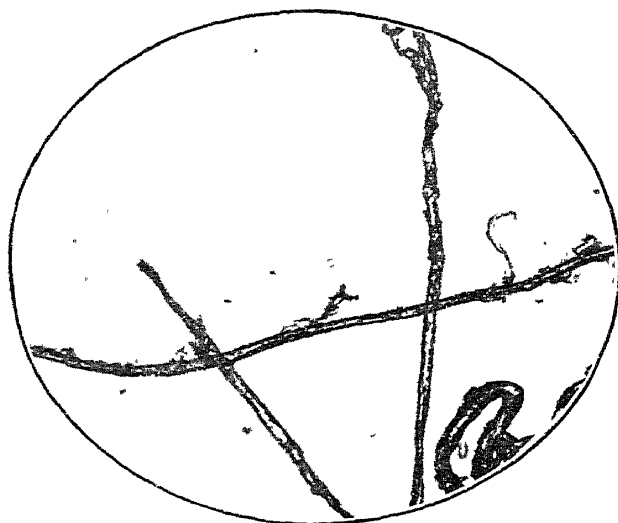
FIG. 71.—PAPER FIBRES FROM ENGLISH CABLE.

Magnified 40 diameters (approximate).
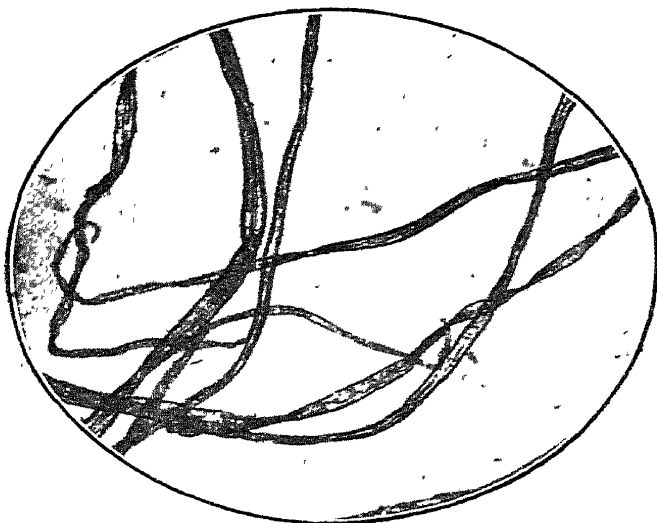
FIG 72 —PAPER FIBRES FROM GERMAN CABLE.
Magnified 40 diameters (approximate)
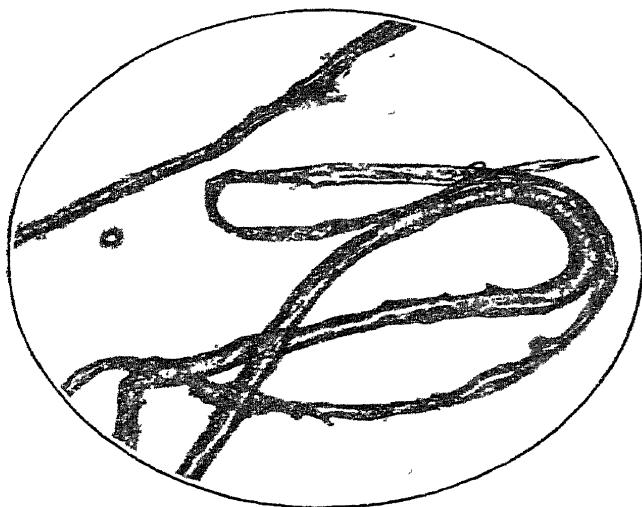
FIG. 73.—PAPER FIBRES FROM ENGLISH CABLE.
Magnified 80 diameters (approximate).
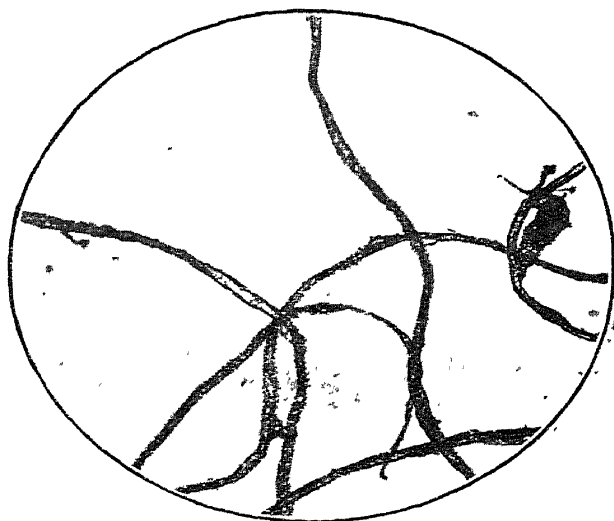
FIG. 74.—PAPER FIBRES FROM ENGLISH CABLE.

Magnified 40 diameters (approximate),
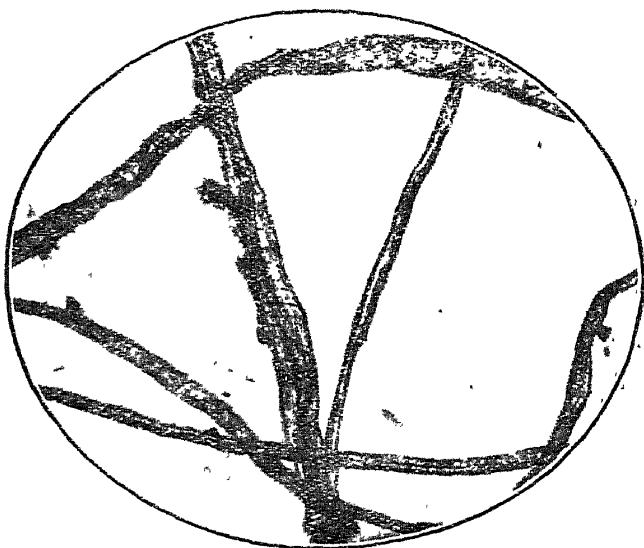
FIG. 75.—PAPER FIBRES FROM GERMAN CABLE.

Magnified 80 diameters (approximate).

Messrs. Beadle and Stevens say, further, that the chief fibre to be *excluded* is jute, which " cannot be regarded as a permanent fibre."

As stated, the undesirable fibres are comparatively easily recognised under the microscope. The following staining solution will help to identify them :—

> Zinc chloride . ... 30 grammes.
> Potassium iodide . .. . 5 ,,
> Iodine. . . . . 1 ..
> Water . . . . 14 c.c.

When stained with this solution, chemically prepared wood fibres should be *violet* or *blue*, mechanically prepared wood *yellow*, " manila " fibres *yellow* or *brown*, esparto grass and straw fibres *blue*, cotton and linen rags *red*. This solution should be regarded as an aid to identification of fibres only, and not be relied upon absolutely.

Some difference of opinion exists as to the use of chemical wood paper , as stated above, it is largely used by German makers. We estimated the paper on a German cable to consist of :—

> Chemical wood . . ... 60 per cent.
> Manila .. . . 30 ,.
> Cells and structureless particles . . ... 10 .,

On an English-made high-tension cable we estimated the paper to consist of :—

> Manila . . ... 80 per cent.
> Chemical wood . . . . 10 ..
> Other fibres and particles 10 ..

Of four English makers' cables we have examined, in two only we failed to find any chemical wood." The rate of deterioration of wood fibre paper is said to be much greater than that of manila paper, under the application of heat : and this becomes of great importance if a cable is liable to be moved after installation, and also with E.H.T. cables, which may be heated by losses in the dielectric. The raw material of manila paper consists of canvas, sailcloth, ropes, hemp refuse.

* It is perhaps only right to say that we have met paper makers who declare that it is impossible even for experts to distinguish the fibres composing a paper

Insulating paper should be strong, tough, thin and put on loosely. These qualities are tested when the complete cable is subjected to a " bending " test. Messrs. Beadle and Stevens' articles mentioned above contain much interesting information on the strength of papers, &c. A strip of 5 mil paper 1 in. wide ought to support a weight of 40 lb., after impregnation.

Impregnating Oil.

The oil used for impregnating the paper is often resin or a mixture of resin, and resin and mineral oils, varying in composition for different makers; waxes and other constituents may be added. We like to see a cable containing plenty of free sticky oil. Such a cable absorbs water very slowly, whereas a cable which does not contain enough oil absorbs water very quickly indeed, and a puncture of the lead means that a long length of cable has to be scrapped before the insulation resistance of the main can be got up to its full value.

The oil used should be as viscous as possible; it should not be so fluid as to flow when the cable is laid on an incline, and it should not get hard enough to crack the paper when the cable is bent in cold weather.

There exists some doubt as to what oils are permissible in a cable insulation, apart from pure mineral and resin oils.[*] Castor oil is used by some British and foreign makers, probably on account of its high viscosity, and such substances as bitumen, resin, ozokerite, ceresin, and paraffin waxes are also used. Oils are divided into drying and non-drying oils (with an intermediate class known as semi-drying). The former thicken on exposure to air by absorption of oxygen; the latter also may alter on exposure and become rancid. Rancidity is said to be due to the action of air and light on free fatty acids in the oil. These acids are produced by the combined effects of moisture and foreign matters in the oil, which act as ferments (enzymes), and which are parts of the seeds from which the oils are extracted. Now, copper and lead are attacked by organic acids, and copper in particular is corroded by rancid fats and greases;

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[*] A foreign cable compound we recently examined consisted of about equal parts resin and resin oil, a mineral wax, like vaseline, and a vegetable oil.

hence it would appear that oils liable to become rancid should be excluded. C. J. Beaver (THE ELECTRICIAN, July 9, 1909) says :—

The development of rancidity does not occur with pure mineral or resin oil, but is chiefly due to the use of fatty oils of vegetable origin. The best British practice avoids the risk of this, as fatty oils are hardly used at all in most impregnating compounds used in this country.

On the other hand, the amount of free acid formed is limited by the amount of fermenting substances present. This is likely to be small, and if large apparently no action would take place inside a lead-sheathed cable, which is sealed from moisture, light and air. Again, the electrical conductivity of oils increases when they become rancid or when they dry. Properly refined castor oil (which is a non-drying oil) will not turn rancid even after long exposure, and ordinary commercial samples generally contain very little free acid. If castor oil were used on the score of expense only, probably a relatively very impure oil would be employed, and this would be objectionable, but to properly refined oil there would appear to be no objection. Resin oil absorbs oxygen on exposure, and becomes acid, whilst resin is itself largely a free acid (abietic), and it is also hygroscopic, but resin and resin oil do not appear to attack copper. In a particular cable, green spots found on the copper conductors were shown to be a salt of copper (perhaps linoleate) formed by some fatty acid developed from the oil, which consisted of about equal parts acid (resin), a vegetable oil, and a hydrocarbon oil or wax. We have seen cables which we supposed contained drying oils, such as linseed, as the compound became gummy and changed colour on exposure to air.

The insulation resistance of paper-insulated cables varies considerably with temperature. This is due to the oil, which becomes a better conductor as it becomes more fluid. This is sometimes observed in taking a first test on cables laid "solid," when the insulation resistance may appear very low. On a second test being made the cable will test normally, the explanation being that the first test was made whilst the bitumen surrounding the cable was still hot.

Cables are now made with the spaces between the strands filled up with oil or other compound. This prevents moisture travelling up the core from a faulty place, as it otherwise

will do. It is a common objection to paper cables that one fault ruins a long length of cable, because of the absorption of water. This is true of some cables only ; if enough compound is put in the cable, water will not travel far along it. The cable to avoid is that type in which the paper, although impregnated is more or less dry to the touch.

Paper-insulated Cables with a Vulcanised Bitumen Sheath.

This class of cable is popular, but it should be used with some caution. The bitumen compound is designed with a view to its waterproofing rather than its insulating properties, though it may also be a good insulator. In buying such a cable one is buying something on trust. There is no test that can prove the permanence of the material. Bitumen is said to be one of the most chemically inert substances, but there seems to be a considerable difficulty in defining what constitutes bitumen. Crude Trinidad bitumen undoubtedly alters with exposure to air, probably losing sulphur. Refined bitumen is Trinidad bitumen freed from water, mineral matter (clay) and sulphur, and then mixed with some kind of petroleum or other oil, which acts as a flux and reduces its otherwise high melting point to a workable temperature of 200°F. to 240°F. Vulcanised bitumen is bitumen or a pitch mixed and heated with sulphur in varying proportions, generally less than 30 per cent.

Generally no cable manufacturer will say what his particular composition consists of, but some of them are stated to contain no bitumen at all.* Probably many such compositions used for paper cables are heavily loaded with mineral matter to make them hard. This kind of protection is liable to crack.

One composition, described as vulcanised bitumen, rather elastic when new, undoubtedly " ages," becoming of a texture that has no coherence, and which breaks rather than cracks when bent.

To give this class of cable the best chance it should be laid solid, thus ensuring the absence of air and moisture from contact with it. It would appear, however, to offer no advantage over properly laid lead-protected cables.

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* Sutherland, *Proceedings* of Faraday Society, December 18, 1903.

Triple-concentric cables of this class used on three-wire continuous-current networks have proved successful even in wet ducts.* The outer conductor is the third wire and of the same potential as earth, so that there is no electrical pressure on the bitumen. For single or three-core cables we should prefer to use this class of cable for alternating pressures rather than continuous. This type of cable was probably designed to overcome the difficulties experienced with lead-sheathed cables from electrolysis, and with vulcanised bitumen cables from decentralisation.

Vulcanised Bitumen Cables.

Much the same remarks apply to these cables as to the last class considered. The buyer is essentially taking something on trust. Every cable maker's composition is
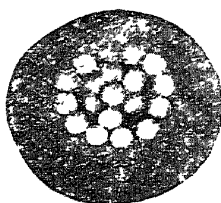
FIG. 76
Enlarged to 1½

secret, and probably different. There is a considerable diversity of opinion regarding the merits of these cables, which is probably explained by the fact that they are used on different kinds of systems and are laid in different ways. When used as the negative conductor of a three-wire system, they have occasionally failed badly. Whole lengths of cable have been found with the insulation rotted, and sometimes the insulation is found to have disappeared altogether.

Some makes of this type of cable undoubtedly decentralise under normal loads. Fig. 67 is a photograph of such a cable decentralised. This cable was in use for about three years,

* Since this was written we have heard of troubles experienced on the networks we had in mind.

and was never loaded up to a current density of 1,000 amperes per square inch. It was more or less decentralised along its whole length (about 100 yds.).

It will be seen from the photograph that there is very little appearance of any external flattening. This, perhaps, is because the heat generated in the copper was only sufficient to render a thin layer of insulation next to the copper viscous. The outer layers of insulation retained their rigidity and prevented any external deformation of the cable. The copper is thus assumed to travel very slowly through the insulation, and it is only when it has very nearly reached the outside that the outermost layers begin to get viscous and to flatten under the weight of the cable.

It is hardly necessary to say that in any length of decentralised cable examined the decentralisation is rarely found to be uniform.
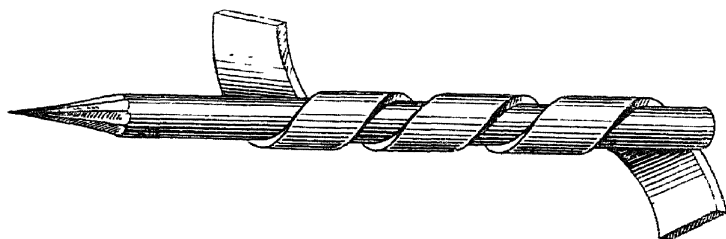
Fig 77.

Another cause of decentralisation which we have seen occur very extensively is apparently due to the contraction of the jute serving wound spirally over the bitumen.* If a piece of tape be wound round a pencil so as to cover it, and if afterwards the two ends be pulled, a spiral space will be left between the turns of tape along the length of the pencil (*see* Fig. 77). The contraction of the spiral jute serving (caused by moisture) leaves a similar space between its turns on the cable, and the bitumen is forced into this space. The cable then has a very curious appearance ; it has shrunk in diameter, and appears

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* We have only seen this effect on cables that have been in use for some years, and we think it probable that the bitumen has generally deteriorated and softened before it occurs, particularly as it most frequently happens to the " negative " cables.

to have a rod of bitumen wound spirally round it. In section it is like Fig. 78, where the jute servings are omitted. The shaded part represents the bitumen, the unshaded part the copper conductor. We have seen a similar action, though to a far less extent, take place on rubber cables. Better impregnation of the jute might at least delay this action; probably a serving of tapes and woven braiding without any lappings of jute would be best. Any external pressure on the cable causes the insulation to lose its shape. This is particularly noticeable with heavy cables, if supported intermittently.

Vulcanised bitumen is readily attacked by alkalies. Now. alkaline liquid is very likely to be found in contact with underground cables used for continuous currents. If a current is flowing through soil its method of conduction is probably entirely electrolytic, and will result in the formation of an alkaline liquid at the cathode; so that the minutest leakage
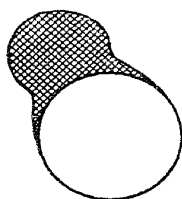
FIG. 78

of current from a joint or fitting on a negative cable will tend to make any moisture round the cable alkaline at that point. Thus, one of the worst enemies of these cables is, unfortunately, one most likely to be present. Of course, the kind of ground in which the cables are laid will influence this.

The physical effect of a strong solution of caustic potash on three different samples of vulcanised bitumen was as follows :—

Sample A.—Thickness of vulcanised bitumen=0·2 in., covering=0·05 in. This was from an old cable that had been in use four or five years. Minute glistening particles could be seen in the compound, probably sulphur. It was only slightly soluble in caustic potash. It was undoubtedly very much altered from its condition when new, being very easily broken, and probably most of its soluble constituents had been already extracted during its service underground.

Sample B.—Thickness of vulcanised bitumen=0·2 in., braiding=0·08 in. A very black and flexible compound. This lost about 20 per cent. of its weight after three weeks' immersion in caustic potash. The residue was rather hard and easily broken.

Sample C.—Thickness of vulcanised bitumen=0·155 in., braiding=0·1 in. Also black, but slightly harder than B. This sample lost nearly 40 per cent. weight after three weeks' immersion. The residue was, however, still flexible.

A length of each of these samples was bent and straightened 10 times round a 12 in. drum and then tested with 460 volts in a metal pail filled with a weak solution of caustic potash. The core of the cable was made negative and the pail positive. A No. 20 lead fuse was in circuit :—

Sample A melted the fuse in 10 minutes.
    ,,   B   ,,   ,,   less than 12 hours.
    ,,   C   ,,   ,,   about 58 hours.

Sample A would probably have broken down without any caustic potash, and is interesting as an example of " ageing " in a vulcanised bitumen cable.

That very strong alkaline solutions do collect round negative faults on cables is well known. Metallic potassium and sodium are frequently found on a negative fault. This is more particularly evident when the fault current has to pass through some porous material, such as bricks or concrete, which may exercise some selective action.

An analysis of the salts found round a negative fault on a solid laid cable supplying a workhouse at Liverpool was given in a Paper read by Mr. Henry Bassett, jun., before the Society of Chemical Industry, and reported in THE ELECTRICIAN for April 12, 1907. The analysis was as follows :—

KOH=33·37 per cent., NaOH=32·26 per cent., K, liquid alloy=1 per cent., Na, liquid alloy=0·80 per cent., soluble silica=4·80 per cent., sand and earthy matter=26·36 per cent., bitumen and water=1·41 per cent. About 1,000 grammes were found altogether. The soil in which the cable was laid was sandstone, which contained 0·047 per cent. potassium oxide and 0·016 per cent. solium oxide. The surface soil contained 0·056 per cent. potassium oxide and 0·055 per cent.

so.lium oxide. Mr. Bassett calculates that the amount of alkali given to him (650 grammes) could have been obtained from $\frac{1}{3}$ cubic metre of sandstone, or from $\frac{1}{5}$ cubic metre of the surface soil.

It seems possible that the soil immediately below a macadam road may be much richer in potash and soda than agricultural land. An analysis of a good loamy soil gives about 0·8 per cent. potash and 1·5 per cent. soda. An analysis of a piece of granite gives 6 per cent. potash and 2·5 per cent. soda ; basalt 1·3 per cent. potash and 3·9 per cent. soda ; whinstone 3 per cent. soda and a trace of potash. It is probable that the continual grinding action of the traffic on a macadam road will cause the stones to decay much more quickly than when only exposed to ordinary weathering influences, and hence the soil below the road may come to contain relatively considerable amounts of potash and soda in a soluble form.

It is possible that the fall of insulation resistance* with temperature may account for the observed failure of vulcanised bitumen cables, when used for the negative side of a three-wire system. Other kinds of cable have failed in a similarly wholesale way, but a reason can nearly always be given, and the failure could have been prevented by a different method of laying. That the duct containing the faulty cable is generally wet and dirty must be regarded as a result of the cable failing, and not the cause, as adjoining ducts containing positive and third-wire cables will be found quite dry. (In this connection, *see* discussion on Mr. Highfield's Paper, " Transmission of Energy by Direct Current," *Proc.* I.E.E . Vol. XXXVIII., p. 528.) Nearly all insulators conduct electrolytically at high temperatures. The complicated structures forming the molecules of vulcanised bitumen split up, and the ionised molecules so formed drift under the potential gradient, the one group to the anode the other to the cathode. Thus a current flows through the insulation, part of its path, until it reaches the third wire earth, being through soil. Now, as explained above, the effect of this current (however minute)

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* " Vulcanised Bitumen cables . . . . . do not compete with other classes of cables in measurable insulation " [Report of Departmental Committee on Electric Mains Explosions, *see* THE ELECTRICIAN, July 10, 1914.]

will be to collect an alkaline liquid round the cable. If this really does happen, the insulation will be attacked at this point and made thinner; the next time the cable is heated up a slightly larger current will flow and more thinning will take place; the destruction will be progressive.*

It also seems possible that moisture may be actually forced through the insulation by electric osmotic force, whenever the insulation resistance falls.

In " Electric Motive Power," by Albion T. Snell, p. 307, the author writes : " The latter class (V.B. cables) is cheaper, and hence is more suitable for large trunk mains ; but, since it rapidly *loses its insulating properties if in contact with water,* it is necessary to encase the compound with lead."
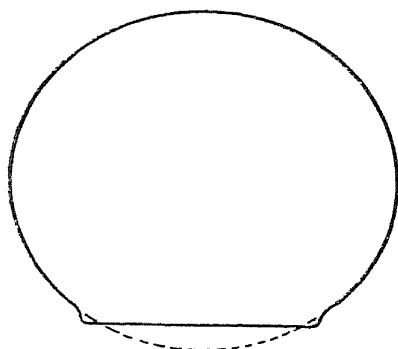
FIG. 79.—DIAGRAM OF V B CABLE SHOWING INCIPIENT FAULT.

The actual current flowing will be exceedingly minute. For, suppose the resistance of a mile of cable reduces from 75 megohms to 1 megohm when heated up, the leakage current (with 250 volts) is only $\frac{1}{4000}$ ampere. This current, however, is not distributed over the whole circumference of the cable, but only at points where it is supported on a not very good insulator (say, a wet wooden saddle).

In further support of the theory suggested above, it may be said that V.B. cables have been, so to speak, caught in the act of breaking down. For instance, Fig. 79 shows the outline

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* This view of the failure of V.B. cables has been disputed by C. J. Beaver (*see Jour.* I.E.E., Vol. 53, p. 75).

of the circumference of a 0·5 V.B. cable (actual size) that had been in use as the negative of a three-wire system. The insulation at the flattened part was cracked on the outside and permanently soft, the insulation being apparently normal nearer to the conductor. Such a soft condition can be exactly imitated by treatment with caustic soda. The fact of the softening starting on the outside and working inwards appears to show that it is due to some external cause, such as attack by alkalies ; if the presence of the alkalies is not due to leakage current through the insulation, why is it that the positive cable in an adjoining duct was exempt from all such attack ?

We have been informed by jointers accustomed to work with V.B. cables that a difference may sometimes be noticed in the condition of the insulation of the positive and negative cables after some years' service. The positive insulation tends towards brittleness, the negative towards a consistency resembling that of cheese.
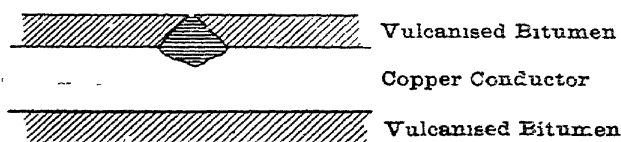
Fig. 80.—Diagram showing Fault on Positive Bitumen Cable.

A further point may be noticed. If the destruction of these cables is due to electrolysis, the attack on the insulation of the negative cable should be from the outside inwards, and on the positive cable from inside outwards. This is exactly what does happen. On examining a faulty positive cable, after the braiding is stripped off, and if the fault has not gone very far, a small green spot is perhaps the only sign of trouble. If, however, the insulation be pared down at this place with a sharp knife, the green area will be found to increase progressively down to the conductor, which will be found to be corroded (*see* Fig. 80). The salt formed is generally green, but sometimes blue , it is only partly soluble in cold water and has an acid reaction.

A metallic sheathing completely enclosing the insulation should protect it from all soil electrolysis. Steel armouring

would not accomplish this, as any stray earth current might deposit alkaline liquid on the armouring itself, which would soak through the interstices, and so attack the insulation. The armouring would have to be very frequently and efficiently earthed to prevent the possibility of this, a very difficult thing to do, in a coal mine, for instance.

It is said that decentralisation is sometimes a manufacturing defect, occurring at the ends of coils, where the cable is hand guided. It seems probable that manufacturers who found this to occur would always reject the few feet at the end of each coil.

In fixing this class of cable great care should be taken to avoid all external pressure. The bearing surfaces should be as large, and all bends made as easy as possible Abrupt changes of level in small manholes are fatal. Like lead-covered paper cables, they should be handled with caution in cold weather, as the insulation of some, at any rate, cracks very easily

We think vulcanised bitumen cables should be laid solid if used for continuous currents, and are more suitable for alternating currents, as in three-phase mining work. If they must be drawn in, insulating and watertight, or metallic ducts should be used, or concentric cable, the outer conductor of which is at earth potential.

It is a great advantage to have the core filled up solid with bitumen, which prevents moisture travelling up its interstices..

There are many different makers of these cables, and they probably all use different formulæ,* so that some may stand quite well under the conditions in which others have been known to fail. As stated above, the difficulty is to predetermine the behaviour of such cables under given conditions.

The insulation resistance is of the order 50 to 200 megohms per mile ; the larger the cable is the relatively lower is the insulation resistance. The lower limits of insulation resistance

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* One make of cable is said to consist of 50 per cent. Trinidad bitumen, 40 per cent. cotton seed pitch, and 10 per cent sulphur. C. J. Beaver has given an account of the breakdown of vulcanised bitumen cable in tropical countries (*Jour.* I.E.E., Vol. 53, p. 75).

for all-bitumen cables are approximately 100 and 50 megohms per mile respectively for 0·1 sq. in and 1 sq. in. cables.

Vulcanised bitumen cables are made with rubber and paper separators next to the copper. Probably both these cables are more reliable than all-bitumen cables.

Rubber Insulated Cables.

Rubber cables are made with a layer of pure rubber next to the copper ; above this is a layer of vulcanised rubber. The copper must be tinned, otherwise the oxygen absorbed in it will attack the rubber

Rubber cables were at one time largely used for high-pressure currents ; for this purpose they are now almost entirely superseded by paper-insulated cables in this country, but lead-sheathed rubber cables are still common in America for all classes of work

Rubber cables are extremely variable in their behaviour, but if ot good quality and kept dry and cool they should have a long life.

Seven or eight years would appear to be about the life of low-tension rubber cables drawn into wet ducts The deterioration of rubber is a process of oxidation. Pure rubber absorbs water readily, vulcanised rubber to a less extent, and in the case of low-tension negative cables this is assisted by electric osmosis. Occasionally water will spurt up 2 ft. or 3 ft. from a negative cable, where the rubber has been slit with a knife, and curious blisters sometimes appear on the rubber. Positive rubber cables are completely oxidised away when they break down for once a slight leakage starts the electrolytic oxygen soon destroys both rubber and copper. Complete severance of the cable is caused, and in earthenware ducts may remain undiscovered for a long time, if the cable is fed from both ends. Unlike the negative cable, the positive seems to break down at points, the rest of the cable being unaffected. When the negative goes wrong the whole length of cable is spoilt. A negative cable saturated with water (always alkaline) may be made to serve quite well for a time as a positive main, being dried out by electric osmosis. It is doubtful. however, if it would last long.

A possible source of trouble with rubber cables used for high-tension currents is a static discharge from the tape covering to earth, which may eventually cause a fault. Where single conductors are used for high pressures it would appear better to use lead-sheathed cables and earth the lead.

One of the chief objections to rubber-insulated cables is the great difficulty experienced in testing the rubber used. A large number of tests have been devised, but it is possible to make a composition which will pass any of these tests individually, and a combination of many of them, and yet be of inferior low-grade material. The rubber next the copper ought to be pure hard Para, and the vulcanised compound over this should have a definite percentage (40 per cent.) of pure Para as a basis, and should contain only sulphur and mineral matter in addition.

The following is an example of the composition of a high-tension rubber cable, made in Germany* :—

Para rubber.	Magnesia usta	Zinc white.	
Congo rubber.	French chalk.	Ceresin wax.	
Litharge.	China clay	Vaseline.	Pitch.

Pitch is specially recommended as adding waterproof qualities.

Probably the adulteration most to be avoided in a cable is "rubber substitute," which is generally vulcanised oil. Mineral loading matter, such as the metallic oxides in the example given above, is permissible, and some (*e.g.*, litharge) may play a part in the vulcanisation process. Vulcanisation consists in the addition of sulphur to the rubber at a temperature above the melting point of sulphur. Usually there is more sulphur present than is actually combined with the rubber. The reason for vulcanising is because vulcanised rubber retains its elasticity between far wider limits of temperature than uncured rubber. The chief objects of the layer of pure rubber next the conductor of a cable are to prevent the sulphur in the vulcanised rubber attacking the copper, and to protect the rubber against oxygen in the copper.

Unlike vulcanised bitumen, vulcanised rubber is not dissolved by alkalies. We have steeped rubber insulation taken

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* Heil and Esch, "The Manufacture of Rubber Goods."

from high and low-tension cables in strong caustic alkali solutions for many months, and the rubber seems to be only very slightly dissolved. It, however, swells up, and perhaps becomes more elastic. Comparatively hard and cheap rubber cables, used for continuous current in wet ducts, appears to last better than a presumably purer, more flexible and more expensive cable, possibly owing to a smaller absorption of water. Rubber undergoes a continual slow deterioration; apart from this, the failure of rubber insulation is due to the combined effects of electrical pressure and moisture.

During the discussion on a Paper on " The Electric Wiring of Buildings," read by Mr. Chamen to the Institution of Engineers and Shipbuilders in Scotland, Mr. M'Whirter mentioned
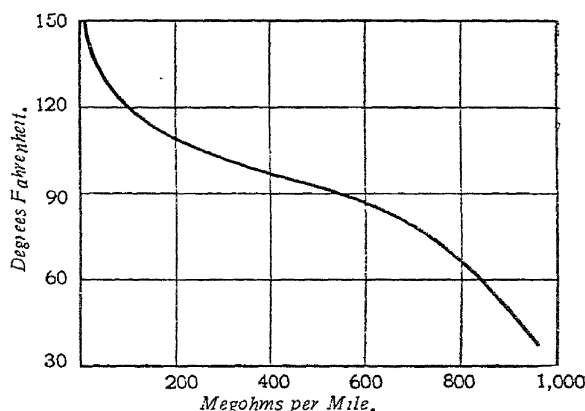
Fig. 81.—Showing Change in Insulation Resistance of a Rubber-covered Cable with Temperature.

some rubber cables laid in the Persian Gulf and other tropical places, " which did good service, and after a long period were found to be as good as ever; so that it could not be said that deterioration was all owing to heat, because there the temperature would range up to 100°F., and it could not be said that it was due to moisture, because these cables were totally submerged." These were telegraph cables, and so were subjected to a very small electrical pressure. Condensed moisture is specially deleterious in its action on rubber, and this would indicate that the action which takes place is not mere absorption, as a sponge takes up water, but rather a.

chemical, or perhaps an osmotic, effect.   Rubber can be made to act as a semi-permeable membrane to many organic substances in an osmotic cell, although not permitting water to pass.

Rubber cables should be kept dry, particularly when used for continuous currents , there is far less trouble with rubber insulation used on alternating circuits than there is on continuous current-circuits.   In this connection, cables rendered fireproof with some alkaline salt, which is often deliquescent, should not be drawn into ducts or pipes.   Such cables are liable to fail rapidly when the braiding is earthed.

The insulation resistance of rubber varies with temperature and the amount of variation is said to be an indication of the amount of Para rubber present.   In some samples the curve connecting insulation resistance and temperature has a double curvature (as shown in Fig. 81, due to Fisher).

Braiding.

A protective serving of jute is often applied over the lead soaked in some preservative compound, generally of a tarry nature (often Stockholm tar), or the preservative may be non-inflammable.   Cables that are intended to be drawn into ducts should have this covering woven on in the form of a braiding, and not simply wrapped on spirally.   When the serving is put on in the latter way it will often " ruck up " when being pulled round a bend, and after a few feet of it have been stripped off it will be found impossible to get the cable any farther.   Braiding increases the cost of the cable rather considerably for small sizes.   It is important that the braiding be thoroughly impregnated.

Armour.

Armouring is of steel tape or of galvanised iron or steel wire, and served with two coatings of impregnated jute.   Probably steel tape affords the better mechanical protection, but it is recommended that cables with a diameter over the lead of less than 0·5 inch should be wire armoured.   The losses in armoured cables when used for alternating currents may be minimised by including one bronze wire amongst the iron wires, thus breaking the continuity of the iron.

An iron spike driven into the ground or a lusty blow with a pick will always pierce ordinary cable armour, and in some soils it rusts away very quickly, a heavy clayey soil appearing to preserve it best. A light sandy soil is not so good, as the steel is alternately exposed to water and air, which percolates through such a soil. " Made-up " ground, especially if it contains ashes, is probably the worst of all. Occasionally the steel armouring in such ground will be found to have completely disappeared, and this is also the case in some coal pits. For " made-up " ground the use of sand may be an advantage. When cables are exposed during drainage or other operations it is important to see that ashes and other rubbish are not filled in round the cable. This is often done in very wet weather when the soil taken out cannot be put back and rammed, owing to the elastic spongy state it assumes. We were informed recently by a man whose duty it is to see all openings of the road in a certain town that gas pipes are as a rule much more corroded than water pipes and this agrees with the authors' own observations Possibly this difference is due to the low temperature at which water pipes are maintained. The life of steel-tape armouring is considerably lengthened by having the jute servings liberally impregnated with sticky compound.

Lead Sheathing.

Pure English lead is generally specified for cable sheaths. Lead of 99·9 per cent. purity is easily obtained, but lead of commercial purity is employed in practice, containing traces of antimony, &c. The lead sheath of a cable is really tested in the bending test ; it should not be applied too tightly to the cable, nor yet too loosely. Tin is added to the sheathing of telephone cables to stiffen them, and also because it is said to reduce the chances of corrosion. If lead contains tin, and is bent on a mandrel five times the thickness of the metal, surface cracks develop.*

Graded Insulation.

The systematic grading of insulation has been suggested by various engineers, among whom are Sig. E. Jona, of Pirelli & Co., Milan, and Mr. M. O'Gorman.

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* H. Baucke. " De Ingenieur," Vol. XXIV. pp 163-7.

If a P.D. of, say, 10,000 volts be applied across two conductors in air, which are at such a distance apart that the air is just able to withstand breakdown, then if, say, a piece of glass be placed between, sparks will now pass across, although the glass has a higher resistance to rupture than air. This is because the potential gradient between the two conductors is altered. The gradient becomes steeper in the air part of the insulation, which gives way; this throws an increased strain on the glass, which soon breaks it down. Fig. 82 illustrates this point. The object of graded insulation is, then, to equalise
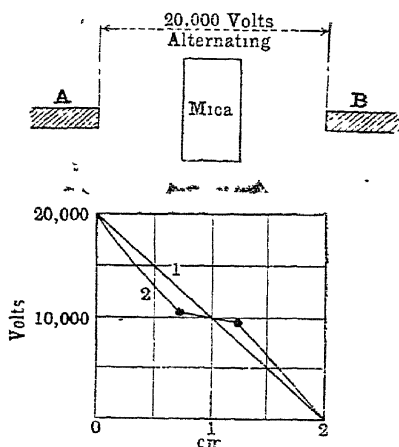
Fig. 82.

1 Potential gradient before the insertion of mica.
2 Potential gradient after the insertion of mica.

the potential gradient, and consequently the electric stress, in the dielectric of a cable to be used for extra-high-tension work.

Fig. 83 shows a section of a cable. The fall of potential in the dielectric will be proportional to the resistance of each layer, AB. Now the resistance of the layers varies with their distance from the conductor, those layers (A'B') nearest the conductor having the highest resistance. Therefore the rate of fall of potential will be greatest next to the conductor and diminish as one proceeds to the exterior of the cable. Consequently the layers of dielectric next to the conductor have to stand the greatest strain. This assumes a uniform dielectric. In order to make the potential gradient uniform the specific

conductivity of the inner layers may be made greater than that of the outer layers. If this be done properly a uniform fall of potential may be obtained from the conductor to the sheath, which permits of a thickness of insulation being used in direct proportion to the voltage. In building a cable in this way care must be taken not to alter materially the specific inductive capacity as well as the conductivity. Cables to be used for alternating currents may be graded by varying the specific inductive capacity of the different layers. For considering again Fig. 83, each layer may be supposed to consist of a condenser, successive layers representing so many condensers in series. Now the charge on a condenser is $q = CE$, where q=charge, C=capacity, E=potential. Since
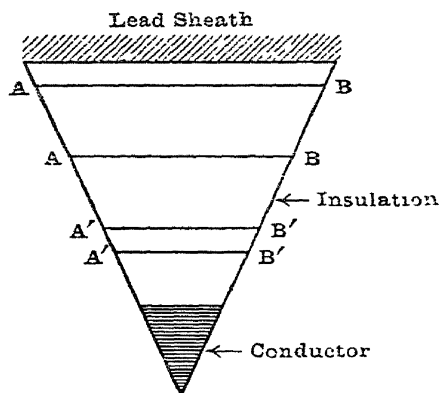
FIG. 83.

all the little condensers get the same charge, and since C increases for each condenser, as one proceeds outwards from the conductor, E, the potential across each condenser must get less the further away from the conductor one goes. If by any means C can be made the same for each condenser, then, since q is the same, E must also be the same.

The capacity of a condenser is

$$C = \frac{AK}{4\pi d},$$

where A=area of plates, K=dielectric coefficient, d=distance between plates. Since A increases and d remains constant,

K must be made to decrease in proportion as A increases.. An example of a cable graded in this way was exhibited at the Milan Exhibition in 1906 by the Pirelli Co., of Milan, built for a working pressure of 100,000 volts (*see Electrical Review*, July 20, 1906). This cable consists of 19 strands of a total section of 162 sq. mm. The strand is covered with a lead tube in order to produce a smooth surface. An uneven surface causes an increased strain in the neighbourhood of projecting points.

The first layer is of rubber 2·5 mm thick, K=6·1
The second ,, ,, 2·3 ,, ,, K=4·7
The third ,, ,, 4·5 ,, ,, K=4·2
The fourth ,, impregnated paper
5·2 mm. thick K=4·0

Over the paper is wound hemp and over all a lead sheath. The diameter over the lead is $2\frac{5}{16}$ in.

Mr. O'Gorman's (*Proc.* I.E.E., Vol. XXX., p. 608) and Mr. Russell's (*Proc.* I.E.E.,Vol. XL., p. 6) Papers should be referred to in connection with extra-high-tension and graded cables.

E.H.T. Cables.

The problem of the extra-high-tension cable is not yet completely solved. Three-core ungraded cables are working at 20,000 and 30,000 volts,* and their manufacture, with a reasonable overall diameter, presents no great difficulty. The insulation thickness for these voltages varies from 0·5 in. to 0·75 in. A 40,000-volt three-phase cable used in Italy has conductors each 50 sq. mm., and 14 mm. of insulation between conductors, and between conductors and lead. Theory shows that the electric stress at any point in the dielectric of a single or concentric cable is determined by

$$\text{Stress}=\frac{V}{x \log_\epsilon\left(\frac{R}{r}\right)},$$

where V is the applied voltage, x is the distance of any point from the axis of the cable, r is the radius of the conductor

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* Pressures higher than these are in use also ; single cables working at 100,000 volts are used for continuous currents

and R is the inner radius of the lead sheath or outer conductor. This expression has its maximum value when $x = r$.

$$\text{Max. stress} = \frac{V}{r \cdot \log\left(\dfrac{R}{r}\right)} \; ; \quad \text{or Max. stress} = \frac{0 \cdot 434 V}{r \cdot \log_{10}\left(\dfrac{R}{r}\right)}.$$

By differentiating it may be seen that so long as r is less than $\dfrac{R}{\varepsilon}$. the max. stress will diminish as r increases.

The fall of potential across any layer of the dielectric varies as the reciprocal of the capacity. The capacity of any concentric layer of insulation is

$$\text{Capacity} = K \frac{k}{\text{Log}_{10} \dfrac{D}{d}},$$

where $k =$ dielectric coefficient, $D =$ outside diameter and $d =$ inside diameter, $K =$ constant.

Now both these expressions may be easily verified experimentally, by using a triple concentric cable, or by making a cable with copper foil inserted in the insulation ; but when it comes to breaking down cables it is found that they do not always behave as expected. For example, if two cables be made with the same radial thickness of insulation, but with conductors of different diameters, for any given voltage the cable with the smaller conductor is subjected to a greater maximum stress than the cable with the larger conductor and yet the actual breakdown (R.M S) voltage of each may be, roughly, the same.

There are great difficulties attending the determination of the true breakdown pressures of cables, and it may be that with increased precautions practical results will be made to agree with the maximum stresses as calculated. In the meantime it looks as though the maximum stress, as calculated, is not the only factor which decides the breakdown of paper insulated cables. Oil impregnated paper insulation is not a homogeneous substance, but consists of alternate layers of impregnated paper and films of oil, two substances which

have different dielectric coefficients. We have noticed if the paper insulation is wound on very tightly (which makes a non-flexible, inferior cable), so as partly to exclude oil films between the layers, that then the calculated maximum stress at breakdown is more nearly constant. At present E.H.T. cables are designed more from experimental data, combined with long experience in the details of manufacture than from purely theoretical calculations.

The resistance to rupture of oil impregnated paper is about 20,000 volts per millimetre. It is not practical to increase the thickness of the insulation without limit, partly on account of
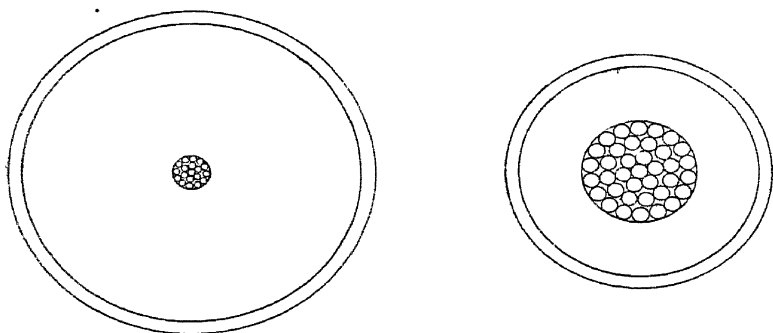
Fig 84.—Single-core 50 sq. mm and 500 sq.mm. Cables with Equal Specific Stress of Insulating Material *

flexibility, and partly because of the difficulty of impregnating the inner layers of paper. Also above a certain point the maximum stress is very slightly decreased by an increase of the thickness of the insulation. We anticipate that cables insulated entirely with oil and paper will be made with graded insulation in the near future, and then long cables to work at 50,000 volts certainly, and probably at 100,000 volts alternating pressures will be a commercial possibility.

Fig. 84 shows two cables insulated for equal stresses in accordance with the formula given above.

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* From a Paper by R. Apt. *See* The Electrician, August 14, 1908.

Power Factor of Cables.

The nature of the loss in the cable dielectric is disputed, but recent experiments * appear to show that the view first propounded by C. P. Steinmetz, that it is a *dielectric hysteresis,* analogous to the hysteresis of iron, more nearly represents the facts than the other view which regarded the action as in some way due to conduction in the dielectric. Thus it is supposed that the cycle of operations comprised in electrifying the dielectric, discharging it, electrifying it in the opposite sense, and again discharging it, requires a consumption of energy, actually dissipated as heat in the dielectric, and due to some kind of internal friction opposing electrification. The absorption current and the residual charge † in a cable depend on the power factor.

Fig. 85 is taken from Höchstädter's Paper, and shows the method of calculating the dielectric loss from oscillograph records. It will be seen that the maximum value of the voltage occurs simultaneously with zero value of current, but that the maximum value of the current does not coincide with the minimum value of the voltage. The charge curve is obtained from the current curve by measuring the area enclosed between successive sections of this curve and the horizontal axis [$Q = \int i\,dt$]. The curve obtained by plotting charge against volts gives a closed loop, similar to the hysteresis curve of iron ; the capacity of the cable corresponds to the permeability of the iron.

Manufacture of Paper Cables.

A brief account of the manufacture of a paper insulated lead sheathed cable may be of interest. The copper core, being stranded up in a stranding machine, is passed through an insulating machine, where the layers of paper are lapped on spirally to the required thickness. The reels containing the (technically wet) paper cable are now put in a steam-heated oven for some hours, where a part of the moisture is

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* M. Hochstadter, *Elektrotechnische Zeitschrift. See* THE ELECTRICIAN, September 2, 1910.

† *See* notes on Testing Insulation Resistance, Chap. II., Part II.

Dielectric loss= 5015 − 4655 sq mm
= 360 sq mm
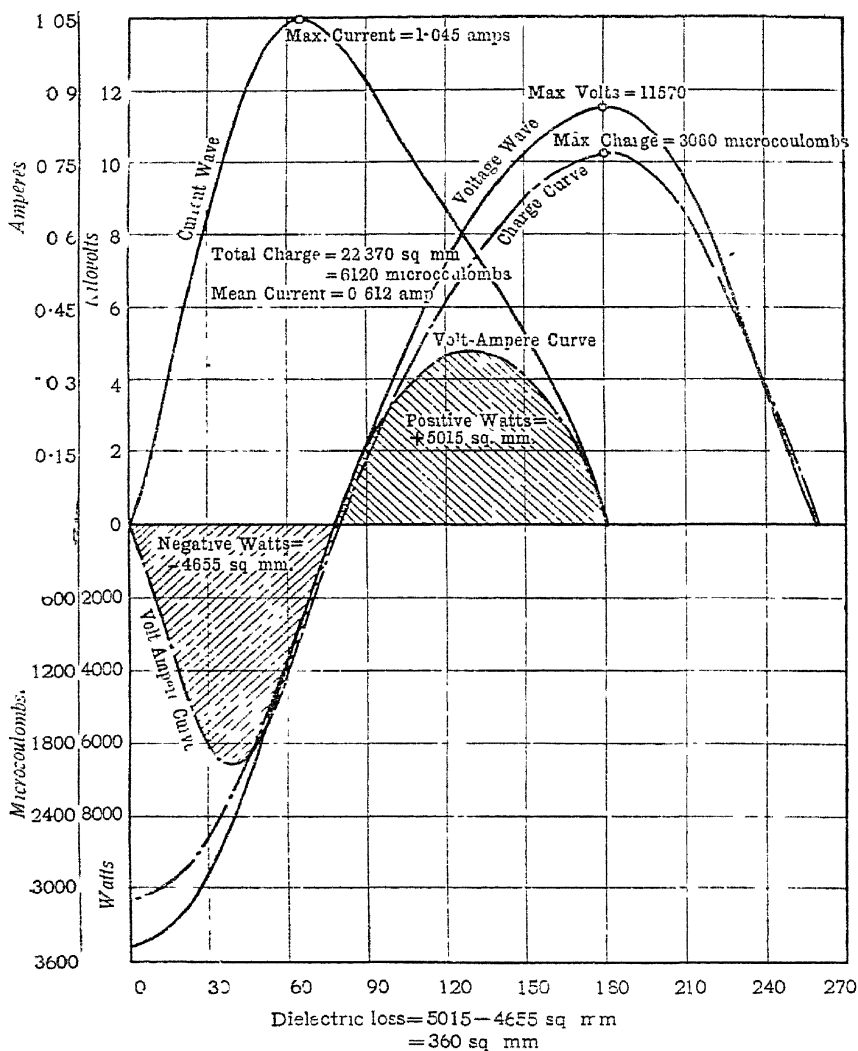
i e, dielectric loss per km =199 watts , capacity calculated from maximum values of charge and volts per kilometre $=\dfrac{3060}{11570 \times 0.67}$

= 0 394 microfarad.

Frequency= 50.   Length of cable = 670 metres.

FIG. 85.—CALCULATION OF OSCILLOGRAM.

extracted. Care must be taken not to overheat the paper at this or any stage. The hot cable is then put into a vacuum oven, also steam-heated, in which an air-pump maintains a vacuum of about 26″. After a (varying) time, water begins to drip over into a condenser connected with the oven, and may be observed through a glass window. When water ceases to come off (in from 5 to 15 hours), the cable is regarded as dry, and oil is admitted to the oven completely covering the cable. Air is next admitted above the oil, in which the cable remains for a period, varying with the thickness of the paper insulation. When it is considered to be properly impregnated the oil is drained off and the oven opened ; the cable is then taken direct to the lead press and covered. Another method of impregnating a paper cable consists in impregnating the paper before it is applied to the conductor. It is claimed for this method that it produces greater uniformity than the one first described. We do not think there is much in this claim, as the first method gives perfect uniformity, provided the oil gets right through the insulation. Cables in which the oil has not penetrated are of course rejected, this point being easily settled by a high tension test, which can be arranged to break down a cable if there is any dry paper in it.

CHAPTER II.

THE TESTING OF CABLES.

Tests for Rubber Cables.

The following elongation test for rubber used in cables is attributed to the Admiralty, and is stated by Prof. Schwartz (*Proc.* I.E.E., Vol. XXXIX., p. 78) to be " certainly the best in common use."

A 14 in. specimen to be clamped for 1 in. at the ends, and stretched to double its length—*i.e.*, 24 in.—to remain in this state for 24 hours without breaking, and on release, after a further 24 hours, the permanent elongation on the 12 in. length should not exceed 15 per cent. Under-vulcanised rubber is not elastic, while over-vulcanised rubber is brittle. A mixture containing 35 per cent. Para rubber should stand a tension of 750 lb. per square inch before breaking.

From the results obtained from a large number of samples of rubber cables, a stretching test would appear to be a valuable guide to the quality of the rubber. " Association " grade cables were readily distinguished from non-Association. A 5 in. length of cable was taken, the outer braiding stripped off and the conductors pulled out singly with a pair of pliers. The tube of rubber thus obtained was cut to exactly 4 in. in length ; 1 in. at each end was clamped into a holder, leaving 2 in. between the holders. The holders were then separated so as to stretch the sample. This was done by a very slow screw action. Some trouble may be experienced with the clamps cutting the rubber ; these should not be tightened more than is necessary to prevent the rubber slipping.

The following is a typical result for a 2,500 megohm 7/20 " Association " cable :—

Sample No.	Test length. Inches.		Length of stretch Inches		Time of stretch. Hours.		Mean temperature. °F.		Elongation after 24 hours' rest.
1	2	...	6	...	24	...	50	...	26°/₀
2	2	...	6	...	24	...	47	...	25°/₀
3 ...:..........	2	..	6	...	24	...	45	...	25°/₀
4	2	...	6	...	24	...	45	...	21°/₀
5	2	...	6	..	24	...	46	...	20%
6	2	...	6	...	24	...	48	..	24°/₀
7	2	..	6	..	24	...	48	..	22°/₀
8	2	...	6	...	24	...	52	..	21°/₀

7/18–2,500 megohm Association cable (by another maker)

Mean of 8 tests.	2	...	6	...	24	...	52	...	20%

Non-Association 3/20 cable.

1	2	...	6	broken in 13 hrs		—	...	—
2	2	..	6	broken in 5 min.		—	...	—
3	2	...	6	. 24	..	54	..	32°

Non-Association 19/18 cable.

Mean of 6 tests.	2	...	5	...	24	...	54	...	39%

Non-Association grade 7/20 cable (by an Association maker).

1	2	...	6	.. 24	...	55	..	40°/₀
2	2	...	6	broken in 12 hrs.	57	..	—
3	2	...	6	. 24	...	55	..	45°/₀

A German cable, 7/20.

1	2	...	5	broken in 12 hrs.	57	...	—
2	2	..	4½	.. 12 ,,	56	..	—
3	2	...	4½	,, 15 ,,	54	...	—

In the account of a discussion on a Paper by Mr. John Langan read before the American Institute of Electrical Engineers (THE ELECTRICIAN, February 8, 1907) there is a table giving the results of tests on rubber containing different percentages of Para, due to Mr. H. G. Stott. In this table, which is given on next page, the number of samples indicates the percentage of pure Para present. The figures given in the columns show the order in which the different amounts of Para came out in

the various tests. It will be seen that, with the exception of one test, the 40 per cent. Para compound came out best in them all. The others vary more. The change of insulation with test voltage and the insulation resistance temperature coefficient are the only two which give them all in the right order.

	Number of sample.				
	40	35	30	25	17·5
Insulation resistance 20°C	1	2	4	5	3
Insulation resistance, temperature coefficient	1	2	3	4	5
Capacity	1	2	4	5	3
Capacity, temperature coefficient	1	2	3	5	4
Puncture voltage	1	2	3	5	4
Stretch test	1	3	2	5	4
Dielectric time strain test	2	3	4	5	1
Change of insulation resistance with test voltage	1	2	3	4	5
Cost of compound	5	4	3	2	1

Mr. Stott does not include the acetone test, which measures the amount of resinous matter present. It is said that this varies from 2 to 5 per cent. in good rubber.

Another test is that showing the amount of ash left on burning the rubber, but this appears to be of little value, as it represents the amount of mineral loading matter only, and does not discriminate between pure rubber and rubber substitutes. Prof. Schwartz's Papers on " Rubber Flexibles " and " The Testing of Rubber for Electrical Work," read before the Institution of Electrical Engineers, should be consulted in connection with the testing of rubber.

Bending Tests.

It is usual to specify that a cable must be able to withstand a high-pressure test after being bent round a drum and straightened again a specified number of times (5 to 12). ·The diameter of the drum may be from 10 to 15 times the diameter of the cable, or for rubber 5 times the cable diameter. Sometimes the cable has to be bent alternately in reverse directions round the drum, and the pressure test is not always specified, but instead the lead and paper, or other insulation, must show no signs of cracking after the test. The test may be made more severe by clamping the copper and lead together at one

end of the test piece. The bending test ought not to affect the breakdown pressure of a well-made paper lead cable.*

The temperature at which it should be carried out ought to be specified. Drums of cable which have been exposed to a temperature of anywhere about 0°C. over night will probably fail to pass the bending test. The sample piece should be kept indoors at about 15 deg. for 48 hours before the test. Particular care should be taken in handling cables in cold weather, and it is a good plan to put the drums in the boiler house the night before the cables are laid.

FIG 86.
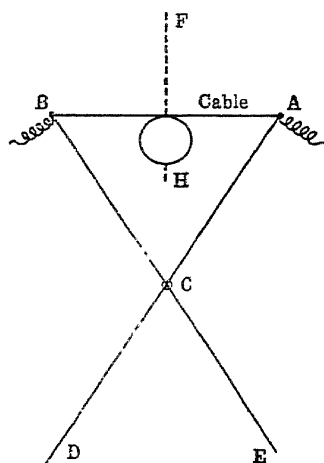
It is more difficult to get concentric cables to pass the test than others, and the diameter of the drum should be at least 15 times the diameter of the cables for this class. If the cables be bent by hand, it is difficult to get consistent results, and it would be almost impossible to condemn a cable as a result of a hand-bending test. A machine is easily made for this purpose, and the principle of one is shown in Fig. 86. The levers BE and AD are pivoted at C, the cable is held in

* C. J. Beaver (*Journ*.I. E E.,Vol LIII., p.63) says that a bending test of E H.T. cables causes an average reduction of the breakdown voltage of 15 to 20 per cent. This statement must apply to a particular make of cable only, as the breakdown voltage of most well made cables is not in our experience affected by a reasonable bending test.

pivoted clutches at A and B, and the wooden drum H is free to slide in the groove FH. To bend the cable the ends of the lever D and E are brought together, and the drum H moved towards F. The drum may be moved by hand, or be connected to the main levers by short pieces; it should so move in relation to the points A and B as to keep the cable always taut. The reverse motion straightens the cable, and the operation may be repeated any number of times in a perfectly definite way.

Insulation Resistance.

There is some doubt as to the exact meaning to be attached to the term " insulation resistance " as generally measured.* It is usual to specify the value as that obtained after one minute's electrification. This is because the reading obtained on a galvanometer is not generally steady, but usually tends to decrease with time—that is, to show an increasing value for the insulation resistance. For example, the deflection obtained on a galvanometer when testing a long high-tension paper-insulated lead-covered cable was initially 32 with a particular shunt, and this had decreased to 15 after 20 minutes' electrification. This is explained by saying that the current as measured on the galvanometer is not wholly a leakage current flowing *through* the insulation, but is in part a current flowing *into* the dielectric and being absorbed by it, and this is called the electrification of the dielectric. There are thus three currents concerned when charging a cable; first the initial rush of current, which depends on the capacity of the cable; secondly, the absorption current, and, thirdly, the leakage current. When testing a cable of high insulation resistance the deflection will be found to decrease quickly at first, and afterwards more and more slowly. Thus the curve connecting time and deflection should be smooth and of a logarithmic shape. It is important when testing cables to maintain the test for 5 or 10 minutes to see that this is so, for if the deflection does

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* *See* Evershed (*Journ.* I.E.E., Vol. LII., p. 70). " The true dielectric resistance of insulation is enormous compared with the actual insulation resistance obtained in practice, and in all ordinary cases we need only consider the leakage which takes place through films of moisture condensed on the external and internal surfaces of the material."

not decrease, or if it varies in an unsteady jerky way, it is an indication of something wrong. With high values of insulation resistance the true leakage current is probably very small in comparison with the absorption current, but with low values the reverse is the case. With low insulation resistance values below 1 megohm the deflection will often be found to decrease with time also, and we have found the curve connecting deflection with time to follow a nearly straight line law. We should not regard this as being due to electrification, but rather as an effect of electric endosmose. It is conceivable that very narrow zig-zag bridges of semi-conducting particles may be formed in the dielectric. The effect of any current passing along these bridges will be to break them, if the particles are of moisture, by electric endosmose, if solid by an action which it has been suggested is the reverse of endosmose.* In either case the effect would be to make the particles travel in one direction or the other, depending on the direction of the testing current, and so to break the continuity of the bridge.

For rubber-insulated cables the insulation resistance will be specified, such as 600 megohms per mile . for paper-insulated cables it is often not specified. The value obtained for rubber cables is an indication of the quality of the rubber. No great importance attaches to the intrinsic value of the insulation resistance of paper cables, the important point is that the value, whatever it is, should be maintained. A high value of the insulation resistance indicates a hard compound, liable to crack ; a low value indicates an oily compound. Minimum values should be from 70 to 140 megohms per mile, the lower value being for the larger sized cables. The insulation resistance of a main laid and jointed up should be equal to the parallel resistances of the cables forming it. This is the valuable figure, which subsequent periodical tests must agree with. Important cables, such as feeders, ought to be tested at least monthly, and any failure in resistance investigated. Sunday is often a convenient day to have the feeders disconnected for this purpose.

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* *Transactions* of the American Electrochemical Society (The Electrician, November 29, 1907). *See* also account of an experiment by Prof. Forbes in the *Electrical Engineer*, February 1, 1907.

We have found generally the insulation resistance of oil-impregnated jute cables to increase in value, this being probably due to loss of oil, the jute getting very dry and brittle. Vulcanised bitumen and rubber-insulated cables more often decrease than remain steady in value.

For very accurate work, and for measuring high values of insulation resistance, a mirror galvanometer is necessary. To make a measurement the galvanometer, battery and insulation, whose resistance is to be measured, are all connected in series, and the deflection of the galvanometer noted $=D_1$. A known resistance is then substituted for the insulation and the deflection noted $=D_2$. The insulation resistance is then $=\dfrac{D_2 \times S_2 \times R}{D_1 \times S_1}$.

S_1 and S_2 are multiplying powers of the shunts used, and R is the value of the known resistance ; if R is expressed in megohms the desired resistance will be given in megohms. The voltage of the battery employed must be high enough to give conveniently big deflections. After the testing leads are arranged, but before the connection is made to the cable, a trial should be made to see if any leakage deflection can be obtained through the testing leads or instruments ; this deflection, if any, must be deducted from D_1. The insulation at the cable ends must be thoroughly cleaned for at least 6 in. To prepare rubber ends the outer tapes and braiding should be taken off, the rubber washed with naphtha and about an inch of the rubber pared down at the end with a clean knife. It should now be dried with a spirit lamp, care being taken not to burn it. To prevent any current that does pass over the surface of the prepared end passing through the galvanometer a guard wire should be twisted on the rubber, the other end being connected between the galvanometer and battery ; and this wire should go on at both ends of the cable if possible (*see* Fig. 87).

A portable testing set must be used for street work. There are several convenient sets on the market. The battery, which generally consists of accumulators, is not a very portable thing, and is usually a nuisance. On a continuous-current system the voltage of supply can often be utilised, or an ohmmeter and portable generator can be employed. An ohmmeter will not give very accurate results if the capacity of the

cable tested is at all considerable. When testing long cables care should be taken not to discharge the cable through the body, as a very unpleasant shock may be had if the testing voltage is, say, 500 or 1,000 volts.

To get consistent results, the cable ends must always be carefully cleaned and dried, and any hygroscopic tapes, &c., trimmed back from the insulation. The same remark applies to the testing leads, which are often a source of error.

A quick method of testing the insulation resistance of sections of network, or single cables, when the value is in any case likely to be low, and a qualitative rather than a quantitative result is good enough, and also when it is important that the cables should be " dead " for as short a time as possible, consists in connecting a high resistance voltmeter between the

FIG. 87.

" dead " cable and a " live " one. If E_1 be the pressure of the " live " cable above or below earth, and E_2 be the voltmeter reading, R_1 the resistance of the voltmeter and R_2 the insulation resistance, then the current

$$C = \frac{E_1}{R_1 + R_2}.$$

From which
$$R_2 = \frac{E_1 - R_1 C}{C}.$$

$$\therefore \quad R_2 = \frac{(E_1 - E_2)R_1}{E_2}, \text{ since } C = \frac{E_2}{R_1}.$$

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If R_1=28,000 ohms. E_1=230 volts, the deflection obtained for a resistance of one megohm is about 6 volts. A Weston voltmeter, reading up to 250 volts. is very suitable for resistances up to 1 megohm.

Cables with a high insulation resistance, sometimes take a considerable time completely to discharge : thus repeated shocks may be got from a cable which has been disconnected from the mains for half-an-hour or more. The potential of such a cable may be measured on an electrostatic voltmeter. We have noticed this phenomenon principally on jute insulated cables,* and it is occasionally an annoyance to jointers working on them ; it may of course be prevented by earthing.

Feeder cables entering a central station are sometimes connected to the switchboard by bare copper strip or rods, supported on insulators, connectors of like polarity being very close together. Under these conditions a disconnected rod may acquire a static charge from the rods between which it is sandwiched, and will give a slight shock on being touched. We found the potential of such a connector, measured with an electrostatic voltmeter. to be 45 volts, the rods on each side of it being 230 volts above earth. Puzzling results may be obtained when testing bare copper strip in culverts or subways, if there are " live " feeders alongside the " dead " feeder being tested. but these effects are produced by surface leakage over insulators, and may be distinguished from static effects, in that they may be measured by a high resistance current voltmeter.

Other effects one may meet with when testing in practice are due to the capacity of cables on alternating current circuits. Thus on a low tension alternating current network, supplying incandescent lighting. if the cables are lead covered and laid " solid." with both poles insulated from earth, a shock can generally be got by touching the lead, unless it is intentionally earthed. and this is greatly intensified if the inner conductor is earthed somewhere. as on a consumer's wiring. In a particular instance, a shock was obtained from a disused gas pipe in a

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* The same effect has also been noticed on cables withdrawn from a duct and lying on the pavement, when the insulation is saturated with alkaline moisture. In these cases the effect lasts for a few minutes only, probably because the insulation resistance is very low.

private house, supplied with 230 volt single-phase current.
The insulation resistance of the house wiring was repeatedly
measured and found to have a very high value, and yet it was
held that a fault must exist on the circuit, since turning off the
main switch, made the gas pipe " dead." This pipe was found
to be in contact, under a floor, with the metal tubing carrying
the lighting wires, and this tubing was electrically continuous,
but not intentionally earthed, and the house being old and dry,
it was probably fairly well insulated from earth ; a bad
" earth " was found to exist on the wiring of a house in the
next road, supplied from the same transformer. Thus, on
touching the gas pipe, a circuit was completed from one pole
through the condenser formed by the lighting wires and the
metallic tubes containing them, through earth to the " earth "
on the opposite pole in the second house ; on removing this
fault, no further shock could be felt, and its possible recurrence
was, of course, prevented by properly earthing the tubing.
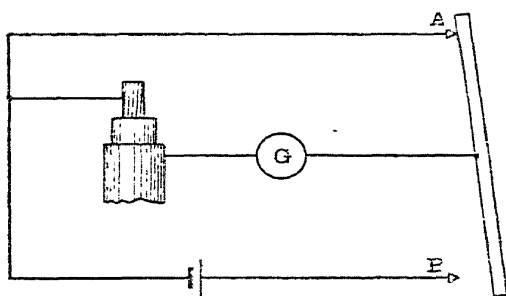
Fig 88.

Capacity Tests.

The easiest, though perhaps not the most accurate, method
of finding the capacity of a cable is to compare the " throw,"
or momentary deflection, of a galvanometer needle when charg-
ing or discharging the cable with the deflection obtained when
charging or discharging a condenser of known capacity.

A mirror galvanometer should be used, and its controlling
magnet adjusted to produce the most sensitive state of the
instrument ; the galvanometer, cable and one or two cells are
then connected up as shown in Fig. 88 with a key, AB.

On depressing the key to B the cable is charged through the
galvanometer G, the maximum deflection is noted, and the

key held in its neutral position, making contact with neither A nor B until the " spot " is again steady ; the key is then depressed on to A and the cable discharges through G ; the maximum deflection is noted again.   The periods of contact of the key with A and B should be as short as possible. This operation is repeated half a dozen times or so, and the mean of all the deflections. both charge and discharge, obtained $=D_1$.   A standard condenser is now substituted for the cable and the process repeated, and a mean reading, D_2, obtained.

Then, if the capacities be respectively K_1 and K_2,

$$\frac{K_1}{K_2} = \frac{D_1}{D_2},$$

$$K_1 = \frac{D_1 K_2}{D_2}.$$

Zelenny and Andrews[*] distinguish between (1) the " true " capacity of a condenser, (2) the " free charge " capacity, and (3) the " ordinary " capacity. The true capacity is defined as the throw given to the galvanometer needle by the free charge in the condenser.   The free charge capacity as the throw given by the free charge plus that given by the absorbed charge that is liberated during the discharge of the free charge. The ordinary capacity is the amount represented by the throw when the condenser remains connected to the galvanometer during the whole period of its throw.   This last value of the capacity is what is measured by the method given above, unless the key is merely tapped on to the contacts A and B and rebounds by its own spring.

Fig. 89 represents the connection between time of discharge and throw of a condenser tested by Zelenny and Andrews. The time of discharge is measured by using a pendulum to make and then break the circuit. This curve shows that after the free charge is liberated, the absorbed charge continues to flow at a uniform rate, for some time represented by the straight line part of the curve, AB ; this line is produced backwards (shown dotted) to cut the axis at C.   If the time of discharge

* " The Capacity of Paper Condensers and Telephone Cables," in the *Physical Review*.

be continued up to the point A, the throw obtained equals the
" free charge " capacity as defined above, and, assuming the
absorbed charge is liberated at the same rate during the time
CA, as it is during the time AB, then the ordinate OC represents
the true capacity. The ordinary capacity of this condenser
was 58·4 per cent. greater than the true capacity, and in the
case of another condenser, tested by the same authors, the
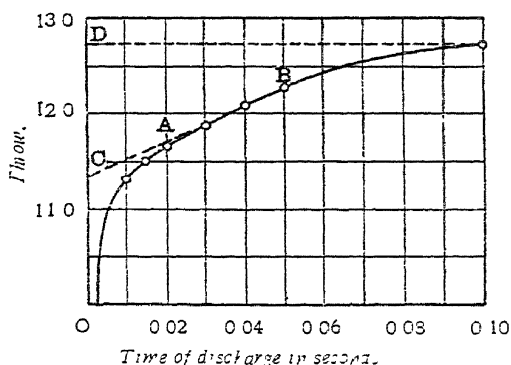
FIG. 89.

ordinary capacity was 281·3 per cent. greater than the true
capacity. The true capacity of a condenser is otherwise
defined as the ratio of charge to voltage.

Maxwell's Method for Measuring Capacity.

Another method of measuring capacity is due to Maxwell,
and consists in forming a Wheatstone bridge connected as
shown in Fig. 90.

C is the condenser to be tested, connected to a rotating
contact maker, indicated at K. G, the galvanometer, is a
moving-coil instrument, with a slow swing compared to f, the
frequency of the contact maker. During the charge the con-
denser forms one arm of the bridge, and the frequency is such
that a steady deflection is obtained on G when the bridge is
unbalanced. The resistance r_3 and the frequency are then
adjusted to produce a balance. Then at every " make " of
the contact maker the condenser is charged with a quantity
$Q=KV$, where K is its capacity and V the potential applied to it,

f represents the number of charges per second; hence the current is fKV. If a resistance, R, formed this arm of the bridge, the current would be $\dfrac{V}{R}$. R thus corresponds to $\dfrac{1}{fK}$. Hence we have, when balance is obtained,

$$\frac{r_1}{r_2}=\frac{r_3}{1,fK} \quad \text{and} \quad K=\frac{r_1}{r_2 r_3 f}.$$

For small capacities $\dfrac{r_2}{r_1}$ may be of the order 5,000, and $f=40$ or 50, and the battery P.D. may be about 50 volts.
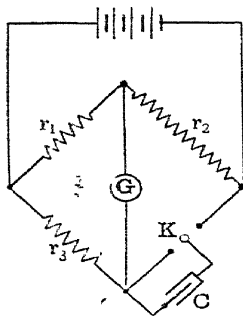
Fig. 90

If a coil be constructed of which the inductance is known,[*] and if an alternator is available, the speed of which may be varied whilst keeping a constant R.M.S. voltage, then the capacity of a cable may be calculated by connecting the coil and the cable in series with a galvanometer and the alternator (or a transformer), and varying the frequency. If the deflections obtained are plotted against frequencies, a very sharp peaked curve is obtained, and the peak of the curve represents resonance conditions, from which the capacity may be calculated. The inductance is known and the frequency is accurately derived from the speed of the alternator. If a

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[*] " Handbook of the Electrical Laboratory and Testing Room." Vol. I. J. A. Fleming.

number of condensers of varying capacity be tried with the same coil, a series of curves will be obtained as in Fig. 91.

Concentric cables insulated with paper of about 0·2 section may have a capacity of the order 0·2 to 0·6 mfd. per mile : if insulated with rubber up to 1 mfd. per mile   Between the outer conductor and lead the capacity will be higher, possibly over 1 mfd. with rubber insulation.
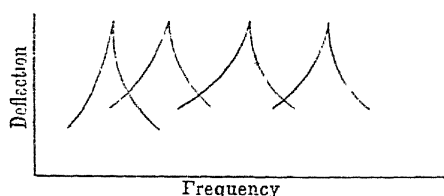
FIG 91

The capacity of three-core cables is for sizes up to 0·1 sq. in. of the order—

Between the 3 conductors joined and lead =0·3 mfd. per mile.
Between one conductor and the other two =0·2   ,,   ,,
Between any two conductors   =0·15 ,,   ,,
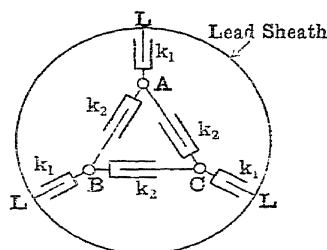
FIG. 92.

The second value varies with the method of connection, being rather higher for star connection than for delta connection. The capacity effects in a three-core cable may be shown diagrammatically as in Fig. 92, where A, B and C represent the three conductors and k_1 and k_2 represent condensers connected between cores and between each core and the lead sheath.

Thus the capacity between the three cores joined and the sheath is $3k_1$, BC and CA in series $=\frac{1}{2}k_2$, and CL and LA in series $=\frac{1}{2}k_1$.

∴ the capacity between any two cores[*] $=k_2+\frac{1}{2}k_2+\frac{1}{2}k_1$
$$=1\frac{1}{2}k_2+\frac{1}{2}k_1.$$

Similarly, between one core and the other two joined, the capacity is $2k_2-\frac{2}{3}k_1$, and the capacity of each core is $3k_2+k_1$.

The capacity of a cable varies with the insulation resistance, increasing as the insulation resistance decreases, probably due to the alteration of the specific inductive capacity, the value of K being 83 for water, of the order 2 for dried paper, and three or four for oil impregnated paper. The capacity may also *apparently* increase with decreasing insulation resistance, due to the larger deflection obtained, caused by leakage current.

A rough idea of the capacity of a cable may be obtained by noting the charging current when an alternating E.M.F. is applied to the cable, from the equation

$$\text{Current in amperes} = \frac{2\pi f \times \text{V} \times \text{K}}{1,000,000}.$$

This is only strictly true for a sine wave E.M.F. For a three-core cable $\text{V} = \dfrac{\text{voltage between phases}}{\sqrt{3}}$.

A 2,000-volt concentric cable about 2,000 yds. long, with a periodicity of 50, was found to take 0·9 ampere on open circuit (Andrews, "*Proc.*" M E.A., 1900).

Measurement of Power Factor.

Great difficulty is encountered in making accurate measurements of such low power factors as cables possess, and it is probably only to be attempted in properly equipped laboratories. The oscillograph method devised by Höchstädter, and given in Chap. I., Part II., appears to be one of the most successful attempts. The most obvious way is to charge the cable through a wattmeter, and with a specially designed

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* The capacity between two cores is the same, whether the third core is joined to the lead or left insulated.

instrument accurate results can be obtained.* The bridge methods, in which the capacity of the cable is balanced against a standard condenser, the cable and the condenser having resistances in series or in parallel with them, require rather elaborate precautions and corrections.

High-Pressure Tests.

Sundry considerations influence the question of what pressure may safely be applied to a cable. A cable may fail immediately a particular pressure is reached, if this exceeds the breakdown limit of the insulation ; or a cable may be able to withstand a given pressure for a short time, but will fail if this pressure is maintained. In this latter case the failure is probably due to heating of the dielectric, caused by the energy losses of dielectric hysteresis. Again the stress on the dielectric at any given voltage is greatest on those layers next to the conductor (see p. 223, and a partial breakdown on these layers is supposed to have the effect of relieving the stress on the rest of the insulation, since it virtually increases the diameter of the conductor. It is, however, possible to guard against being misled by this since the capacity and insulation resistance of the cable will be altered. If, therefore, these measurements be made before and after the pressure test any partial breakdown should be detected. The insulation resistance always drops to a value far below its initial value after a high-pressure test, but it will gradually recover its original value if the cable has not been overstressed. Some doubt exists as to the effect of different frequencies on the breakdown pressure of cables. One view is that the higher the frequency the more severe is the test, but we have not found any appreciable difference between frequencies of 25 and 100. In making the tests it is essential to know the maximum voltage applied to the cable ; the R.M.S. value is generally only a poor indication of the maximum value, and an oscillograph record is useful here.

The object of the high-pressure test is to find out any weak places in the insulation, and for this purpose 2,000 to 5,000 volts is enough for low tension cables. For high tension cables

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* *See* " Handbook for the Electrical Laboratory and Testing Room," Vol. I. By J. A. Fleming.

a testing pressure equal to twice the working value is sufficient, and for extra-high-tension cables the testing pressure may be 50 per cent. greater than the working pressure.*

Pressure Testing of Cables after Laying.

A difficulty, which has only recently become pronounced with the use of higher voltages, is the testing of cables after laying. The Engineering Standards Committee prescribes a test after laying at twice the working voltage. With high-tension cables of any considerable length the apparatus for producing an alternating voltage sufficiently high, becomes very cumbersome, and its transport alone may involve great difficulty. As a consequence the testing of cables with continuous current has been suggested, and in some cases carried out. With regard to the effectiveness of a continuous potential compared to an alternating one some diversity of opinion exists.

A root-mean-square alternating voltage of any given value has a $\sqrt{2}$ times greater puncture value than the same continuous-current voltage, but apart from this, experiment† has shown that a continuous-current voltage has a breakdown value of only one-third to one-quarter the same alternating potential. Until some further experimental work is done on this question. the ratio of continuous to alternating-current values must remain very uncertain for different dielectrics. For example, MM. Laporte and De La Gorge have found for glass 0·5 mm. thick, a ratio of $\frac{\text{cont.}}{\text{alt.}} = \frac{56,300}{8,900} = 6\cdot3$ if the potential is slowly raised, and a value $\frac{21,800}{8,900} = 2\cdot5$, if the potential is suddenly applied ; the same experimenters have found a value for air (2 mm. gap, needles) of 1·1 and for oil a value $< 1\cdot4$. The frequency of the alternating-current potential is also a factor to be considered, but the exact effect of frequency is again not very definite.‡ However, the object of the

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* It is generally specified that the cable shall be immersed in water for 24 hours preceding the high pressure test.

† See *Journ.* I.E E , Vol. LIV., O. L. Record.

‡ *See* De la Gorge and Girault, " Bulletin " de la Société Internationale des Electriciens, Tome II , No. 11, Jan 1912.

continuous-current potential test is to provide a readily portable means of testing E.H.T. cables after laying and jointing. The voltage must be sufficiently great to detect and burn out any weak place due to faulty workmanship or damage done to the cable. It ought not to be difficult to decide experimentally what value this voltage should have for any particular class of cable.

There are several methods of producing a high-tension continuous-current potential. The most obvious would appear to be some form of Wimshurst influence machine. Such a machine has been made by Mr. E. A. Watson (see *Journ.* I.E E., Vol. LIV , No. 260, p. 618), and whilst the first attempt was only partly successful, we believe Mr. Watson has now succeeded in producing a machine of a sound mechanical design, working in compressed air, which will give up to 200,000 volts.

The Delon apparatus is fully described in a Paper by Mr. O. L. Record (see *Journ* I E E , Vol. LIV., No. 260) " The essence of the apparatus is a high-tension contact maker which charges condensers by making at each half period a connection through a short spark between the transformer and condenser to be charged By means of a suitable arrangement the contact is made at the moment when the E.M.F. is at its maximum value, and by means of auxiliary condensers, the voltage of one-half period is added to that of the other, with the result that finally the principal condenser is charged to a pressure double the maximum of the alternating current employed." This apparatus gives a rectified alternating. rather than a strictly continuous potential. It is successfully used on the Continent.

A neat arrangement is made by MM. Geoffroy et Delore, which in its ordinary form will give a tension of from 4,000 to 100,000 volts, but may be made to give a greater tension still. The apparatus consists essentially of an inductive coil, supplied with 6 amps. to 10 amps. through a " mercury turbine," make and break from a source of current, continuous or alternating, at 110 volts. The secondary or high-tension side of the coil is connected through a valve and a liquid resistance (of glycerine and water) to the cable. One form of valve which we have successfully used consists of an aluminium plate and point

about $\frac{1}{3}$ in. apart in an exhausted glass tube. This valve passes current in one direction only, and the cable gradually becomes charged up. Fig. 93 shows the connections.

A purely alternating potential of high value may be produced by using the properties of a resonance circuit. This may be done by placing an inductance in series with the cable to be tested, or if the capacity of this is not of a convenient value, by using additional condensers in parallel with it.

H = Hg make and break
K = Condenser
R = Resistance
R₁ = Liquid resistance

L = Lead of Cable
Va = Valve
V = Voltmeter
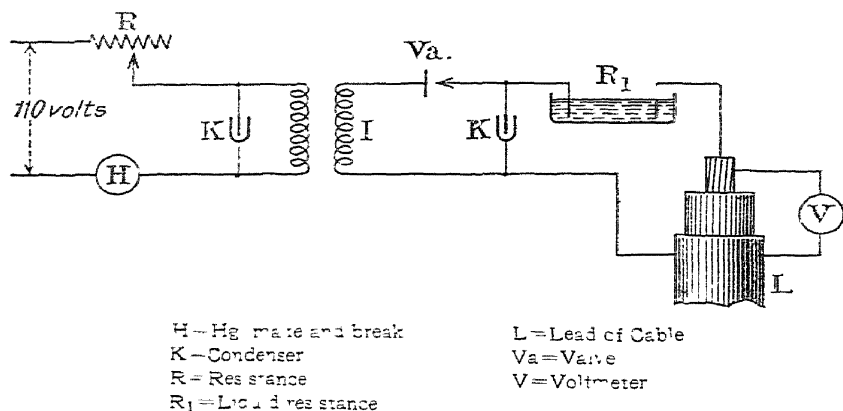
FIG. 93 — CONNECTIONS FOR CONTINUOUS-CURRENT POTENTIAL TEST
(Geoffroy et Delore).

Then if C=capacity, L=inductance, R=resistance of coil, $\omega = 2\pi$ frequency and E=applied pressure ; V, the pressure across the cable is

$$V = E \cdot \frac{1}{C\omega} \cdot \frac{1}{\sqrt{\left(L\omega - \frac{1}{C\omega}\right)^2 + R^2}}$$

(*see* Chap. XI., Part I.).

V is a maximum when $LC\omega^2 = 1$, and $V = E \cdot \dfrac{1}{C\omega R}$ or $= E \cdot \dfrac{L\omega}{R}$.

Hence for V to be twice E, $\dfrac{L\omega}{R}$ must equal two.

Obviously to get high values of V a coil must be used having a low resistance and a high value of L.

A voltmeter should be connected between the lead and the conductor, at the opposite end of the cable to which the pressure is applied, to show that there is no break in it. It will probably be inconvenient to immerse the whole drum in water, and to avoid this a hose can be arranged to play on the reel for a short time. The pressure should be applied and taken off the cable gradually, to avoid rises of pressure. It is only very rarely that a test of this kind finds out any faults in the cable. In a long series of tests the following results were found : a break in the conductor twice. the lead and paper damaged (probably in transit) three times, and once a strand of copper, broken probably in the stranding machine. had partly pierced the paper and the high pressure had broken it down, a previous insulation resistance test failing to show it.

The high pressure test is generally maintained for 15 or 30 minutes. A large number of drums of cable can be tested at once connected up in parallel. When testing long lengths of high-tension cables with high voltages the large charging current is a disadvantage, and to compensate this, on the County of Durham system, a choking coil is connected between the cable and earth. The testing transformer has thus only the losses in the cable to supply.

Conductivity Test.

In some cases a drum of cable will fail to pass this test. The conductivity of the copper may be up to standard, but some or all of the strands may not be of the right section. It is usual to specify that the copper in cables shall be of a definite conductivity (100 per cent Mathieson's standard at 60°F.*) : but it is more important to know that the resistance of the cable is equivalent to that of a solid copper wire of the specified area and conductivity, so that the measured resistance of any definite length at a definite temperature is no higher than the calculated resistance of a cable of the specified cross-section.

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* Or equal to the standard specified by the Engineering Standards Committee (*see* Chap. I.. Part II.).

As cables are sold by length, it is of no very great importance if a cable is brought up to standard by the use of a few strands of slightly increased gauge, some of them being below the specified conductivity.

To measure the absolute conductivity every strand must be separately gauged, which is itself tedious enough in a large cable : an allowance of 2 per cent. must afterwards be made for the " lay " of the cable. The effect of the lay of the cable is to increase the resistance, because the current flows along the separate conductors and not straight through from strand to strand. If the current did flow straight through, the resistance of a cable composed of spiral strands would be less than the resistance of the same number of straight wires. The contact resistance between strands is increased when the core is impregnated with oil or other compound. With large cables it is not permissible, owing to cost, to use a long length for testing, and consequently an accuracy to 1 per cent. is all that can be expected.

With the equivalent area at specified conductivity test it is not necessary to gauge each wire, but the allowance for lay must be made.

The conductivity test is usually made with a potentiometer, and consists in measuring the fall of potential in the conductor, due to a given current. In practice there are a few points to be carefully attended to.

1. The ends of the test length must be sweated solid and the potential leads taken off clear of this.

2. The current passed through the cable must not cause it to rise in temperature.

3. Care must be taken that the correct temperature of the cable is obtained, and for this purpose it should remain at least 24 hours in the room before the test is made.

An allowance of 1 per cent. increased resistance is made on tinned copper wires and a correction made for temperature.

A thing that is often taken on trust is that the stated length of cable is actually on the drum. It is conceivable that a manufacturer might make a mistake in this, which can be checked when the whole of the cable on the drum is to be used at one time. But if short lengths are cut off a drum at different times, especially where a lot of cable is sent out of the

stores daily, it is very difficult to check accurately. If the number of layers of cable on the drum can be ascertained it is an easy matter to calculate the approximate length of cable. The thickness of insulation and lead on a cable are measured with a micrometer gauge, and should be in accordance with the Engineering Standards specification.*

Testing the Compound.

A test for the " fluidity " of the impregnating compound is sometimes specified. It consists in hanging a given length of cable (3 ft. or 4 ft.) vertically for a stated time, say, two days, at a stated temperature and observing whether beads of the compound form at the lower end.

Probably, if the physical properties of the oils are suitable, the chief point to be assured of is their stability and neutrality. The presence of mineral acids (which might be present in vegetable oils if imperfectly washed after refining), and the lower members of the fatty acids which are soluble in water, may be tested for by boiling the oil in distilled water, repeatedly made up, and using methyl orange† as an indicator after the liquid has cooled , this will turn red if acid be present. The amount of acid may be estimated by titration with a standard alkali solution (one-tenth normal KOH). Any free fatty acids present might be estimated by dissolving the oil in ether, or stirring well with alcohol (the fatty acids are soluble in cold alcohol, as are castor and resin oil, but no other vegetable oils to any extent), and using phenolphthalein as an indicator. Unfortunately, this indicator is also sensitive to resin acid, so that if, as is very probable. resin is present. the result would only indicate the *combined* amount of resin and fatty acids, if any. These acids may be separately estimated, but the process is rather difficult. If samples of the cable be exposed to the air (preferably in a living room), with the lead and paper stripped, so as to expose the conductor and oil, for a period of 10 days or so, the presence of rancid oils may be noticed by the compound becoming green or otherwise changing colour, and

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* *See* Chap. I , Part II.

† Methyl orange should be used in this test, not phenolphthalein or litmus

perhaps becoming dry * and gummy. The oil should then be dissolved off the cable—particularly where it is in contact with the copper—with ether : if copper salts are present the solution may be blue or green, as copper oleate forms a green solution in ether and a blue solution when dissolved in alcohol. Or the oil may be well stirred and gently heated with distilled water to which a few drops of nitric acid have been added. This solution will turn blue on addition of ammonia if copper is present. In a particular case the percentage of copper in the oil increased from 0·04 per cent. to 0·61 per cent. after 10 days' exposure of the cable sample.

Resin oil and castor oil may be separated from other vegetable oils by their solubility in cold alcohol. Vegetable oils are distinguished from mineral oils by their acrid smell when strongly heated, and more certainly by saponification with alcoholic potash, the amount of potash used by the fatty acids being determined by titration with standard hydrochloric acid. Thus the compound used in an English cable can generally be separated into resin oil, resin and a mineral oil, by treating with alcohol gently warmed.

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* Resin oil will dry up on prolonged exposure.

Clayton Beadle and Stevens, in a Paper read before the Society of Cellulose and Paper Chemists (May 27, 1909), appear to suggest that resin oil also has a solvent action on copper and lead in the presence of air.

CHAPTER III.

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ELECTROLYSIS ON UNDERGROUND SYSTEMS.

Corrosion of Cables and Pipes.

No general rule can be laid down for the protection of underground cables and pipes from electrolysis. The conditions on every system vary, and each case has to be considered separately. The conduction of soil is probably entirely electrolytic; hence the nature of the soil—the kind of salts which it contains—largely influences the amount of electrolysis. Corrosion chiefly occurs on those cable sheaths or pipes which are at a higher potential than the surrounding soil, and become the anode of the electrolytic cell thus formed. The corrosion of a metal anode is caused by the combination of the metal with a variety of anions, which may be oxygen, OH, NO_3, SO_4, Cl, and other acid radicles. Corrosion of lead results in the formation of various salts, which, if insoluble, will be found at the point of corrosion. Nitrates and nitrites cause a large electrolytic corrosion of lead, but lead nitrate is readily soluble in water, and may, to a large extent, disappear. Lead oxides formed will slowly turn to carbonates by absorption of CO_2. Chalk and other carbonates tend to decrease the corrosion of lead, unless aided by electrolysis, when they increase the action. The corrosion of iron results in the formation of iron oxides. Chlorides tend to increase the action and nitrates to diminish it.

The corrosion of iron depends on whether the surface is active or passive. Iron in the passive state is assumed to be covered with a thin film of oxide (Fe_3O_4) or oxygen, which acts as a kind of varnish and protects it from further corrosion. Iron can be made passive by treatment with nitric acid, so that on re-immersion in the acid it is not attacked, if the surface be not rubbed. Iron is also rendered passive by immersion in molten caustic potash or soda (free from water), and to some extent by immersion in alkaline solutions. The

presence of carbon dioxide, however, may cause passive iron to corrode. In Edison's iron-nickel accumulator, the iron is prepared in a special way in order to make it active. Iron can be changed from the active to the passive state by a high current density. Possibly the mechanism of the passive condition of iron may be similar to the " valve action " of aluminium and other metals with alternating currents.

Action of Alternating Currents.

Intermittent currents may also corrode an iron cathode, by causing alternate oxidation and reduction. (By " intermittent " currents are meant continuous currents, with occasional stoppages of perhaps some hours.) Alternating currents may cause serious corrosion under certain conditions, more particularly of lead. The amount of corrosion depends on a large number of conditions, amongst which are frequency of the current, the nature of the electrolyte, and current density. It would seem that when any irreversible chemical change takes place at an electrode, alternating currents must cause corrosion. For instance, if, when a metal electrode is anode, it forms metal cations ; these may combine with some of the anions to form an insoluble salt, so that the metal ions cannot be re-deposited at the succeeding half waves ; or a soluble salt may be formed in the first instance, which a secondary action may convert into an insoluble salt. For instance, lead plates in a solution of sodium nitrate and sodium carbonate might be converted into lead carbonate by an alternating current, the soluble lead nitrate first formed being converted by a secondary action into the insoluble lead carbonate. It is obvious that the frequency of the current must considerably affect such actions. The rate of diffusion of ions in the electrolyte must also have some influence on the rate of corrosion, for a certain proportion of ions formed may diffuse away from the electrode, thus escaping re-deposition, and causing slow corrosion. The lower the frequency the more this would tend to occur. Also other ions in the solution may be more readily discharged than the metal ions formed from the electrode, thus allowing a number of the metal ions to diffuse away. The corrosion caused by alternating currents is generally less than 1 per cent. of that due to an equivalent

continuous current, but under suitable conditions, the corro-
sion (of lead in particular) may be much greater than this.
In general, increasing frequency decreases the corrosion.
Iron, however, in some solutions is said to corrode more rapidly
as the frequency is increased, probably up to some limiting
value.

Electrolytic Corrosion.

It is a difficult matter to differentiate electrolytic and
chemical corrosion. In the limit chemical a. d electrolytic
corrosion become the same thing. since it is probable that all
corrosion is due to local potential differences. Electrolytic
corrosion generally causes rough irregular patches on the sur-
face of the lead, whilst regular cone shaped holes are sometimes
eaten into the lead by chemical corrosion. Similar shaped
holes are occasionally caused by electrolysis, where the lead
is only touching the electrolyte at points, the holes being filled
with oxide or salts, usually carbonate of lead. Even where
comparatively large patches of lead are affected by chemical
corrosion, the outline of the patch and the depth are generally
regular. Holes are sometimes burnt in lead by arcs. and they
resemble the cone-shaped holes mentioned above.

Current leaves a pipe surface chiefly on the side nearest to
the rails or other cathode, and the amount of current leaving
the opposite side of the pipe, and " bending round," appears
to be inappreciable, judging by the localisation of the corrosion.

A buried cast-iron pipe that has been subject to electrolysis—
one that has formed an anode—is easily recognised. Its
external appearance is not much altered, but if the electrolysis
has been of long duration, the whole of the pipe will be found to
have lost its crystalline structure and all metallic lustre. It
will have somewhat of the appearance of a soft shale, and layers
can be readily prised off with a knife. In bad cases, a penknife
blade can easily be driven through the pipe. Pipes that have
not been subjected to electrolytic action very long have only
the outer skin affected, and when this is flaked off, the metal
underneath is found hard and normal.

On the other hand a chemically corroded iron pipe, such as
one that has been laid in ashes, is entirely different in appear-
ance. It is roughened and pitted, possibly with holes eaten in

it in places, and often shows a variety of colours. Very old gas service pipes often have this appearance. Electrolytic corrosion also sometimes takes the form of pitting ; the appearance of the corroded iron probably depends on the nature of the soil, and to some extent on the kind of iron.

Corrosion due to Tramway Leakage Currents.

Considerable damage has been caused in America and Germany by the return currents of railways and tramways. The usual arrangement is to have the positive 'bus bar connected to the trolley line by feeders, and the negative to the rails, the conductivity of which is normally enhanced by negative feeders. In some few instances the polarity is reversed. The real source of the trouble is the resistance of the return circuit—*i.e.*, the rails. The higher this resistance is, the more current will tend to return from the motors to the station by paths, other than the rails. Thus the latter at points distant from the station will be positive to the earth, while close to the station they will be relatively negative. Earth potential is reckoned as existing at that point in the rails where current tends neither to enter nor leave. Hence at " positive " points current will tend to enter pipes and cable sheathings (hereafter included in the term " pipes "). But where the rails are negative, current leaves the pipes, and it is this district that constitutes the danger area for pipes. Negative feeding points, especially those over-boosted, thus form danger areas. Pipes laid in a uniformly conducting soil will be little affected, because the current density will be low, but pipes, laid in a patchy soil, where the current density is high in places may be greatly affected. There are two ways of looking at the question of buried pipes, the one regards pipes buried in soil as a network of conductors embedded in a comparatively insulating medium. This is approximately true if the soil is very dry, which may be the case if it is well drained and composed of gravel, sand, or chalk. The other way of looking at it, regards the pipes as conductors embedded in a conducting medium of nearly as great specific conductivity as themselves, and this will tend to be realised if the pipes are laid in a wet soil An intermediate condition is probably the actual state of affairs. Earth and pipes together form a shunt to the rails,

and if there is a fall of potential in the rail, some of the current flowing will be shunted out of the rail into the earth and pipes. Messrs. J. G. and R. G. Cunliffe in an I.E.E. Paper,* consider that the current flow is as represented by the arrows in Fig. 94 quite a small proportion of the current flowing in the pipe.

The surface resistance between pipe and earth has been found to equal about 0·2 ohm per square metre, and the resistance of a metre cube of earth to be about 125 ohms.
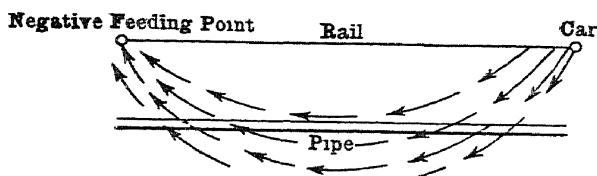
FIG. 94

If the soil is very dry and of poor conductivity, then very little current will be shunted out of the rail, unless special facilities occur for it. For instance, a water pipe laid parallel to the rails might be generally buried in a dry soil, but which contained here and there conducting patches of wet soil. Such patches might be caused by leaky joints in the pipe ; in such a case most of the shunted current would flow in the pipe itself
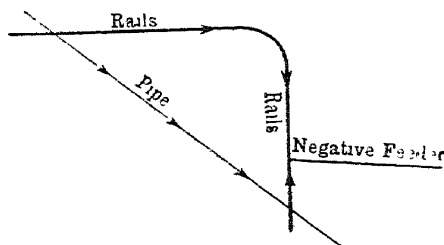
FIG 95.

and corrode it where it left the pipe. Probably pipes which form a " short cut " for the return current are those most likely to carry large currents.

Thus the pipe in Fig. 95 might form part of a circuit of lower resistance than the rails themselves, and thus carry a large proportion of the current.

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* *Journal* I.E E., Vol. XLIII., p. 485.

The potential difference measured between rails and pipes, &c., will in general be a resultant E.M.F., as there are, in addition to the E.M.F. caused by the current, back E.M.F.s caused by polarisation at the surfaces of pipes. Messrs. Cunliffe (v.s.) regard pipes laid at a greater distance than 3 ft. from the rails as out of danger, because nearly the whole fall of potential due to a current flowing in soil is within 3 ft. of the electrodes. If a pipe near the rails differs from the rails by a potential v, then all other pipes further from the rails than this pipe will, if there is no current flowing in them, be also at a potential v with regard to the rails. Similarly if the earth is regarded as a conductor, then if all the fall of potential occurs within 3 ft. of the rails, all earth beyond 3 ft. will be at the same potential, and thus any pipe buried 3 ft. from the rails will be at the same potential as the earth surrounding it, so that no current will enter or leave it from the earth. Yet the pressure between the pipe and rails might be considerable. One case of tramway current corrosion we have seen was on a water valve, about 4 ft. from the rails , the soil was generally sandy. but there was a small leakage of water from the valve. A maximum difference of potential of 3·2 volts was observed between the valve and the rails, but in general it was about 2 volts. the valve being positive The maximum potential difference between pipes and rails observed at Strasburg was 2·8 volts. and the mean 2·2 volts, with the pipes positive. The maximum pressure with the pipes negative was 11·5 volts, and the mean 4·0 volts, and there was " marked corrosion on gas and water pipes made of iron in the danger area, and in un- favourable soil."*

Cables, steel buildings, bridges. water meters, water and gas pipes are all stated to suffer from electrolytic corrosion in America. Insulating joints in pipes are a cause of corrosion, even where the pipe generally is negative to earth, owing to the fall of potential across the joint (" joint jumping ").

In Great Britain a B.O.T. rule limits the allowable difference of potential between any two points on the rails to 7 volts. This prevents corrosion of pipes on the American and German

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* THE ELECTRICIAN, July 20, 1906. " Report of Commission of the German Gas and Water Companies on Earth Current."

scale, but by rendering the action very slow it has the disadvantage of preventing the cause being quickly recognised. The boosting of negative feeders and their cross sections require careful adjustment. Should a feeder take more than its share of current, it will cause a greater difference of potential between the pipes and rails, than when taking a current corresponding to the positive feeder current. Adjustable resistances are thus sometimes inserted in negative feeders, and in Birmingham triple concentric cables were used, so that the resistance of the feeder may be adjusted to suit the traffic.

If all the pipes in the danger areas be bonded to the rails, the current leaving the pipe surfaces will be reduced to a minimum; but this must also greatly increase the current flowing in the pipes, and therefore the " joint jumping " effect and also (as has been found in Germany) the corrosion where two neighbouring pipes cross each other Well bonded rails and a sufficient number of feeding points will largely minimise the trouble.

Mr Paul Winsor speaking at a meeting of the American I.E.E. on electrolysis said .—" The telephone company (at Boston, U.S.A) have taken great pains to survey their cables, and when they find a place where they think there is danger of electrolysis, they consult with our engineers and we put in either a negative feeder or a connection to our rail. This removes the trouble. On our own cables we have cut the lead in many places, made special connections and got rid of the trouble."

Mr. J. W. Corning, also of Boston. at the same meeting, described the results obtained as regards earth currents, by operating certain sections of the tramway system on the three wire system. As would be expected, the rail and earth currents were largely reduced by three-wire operation. For instance, on a certain pipe " under two-wire operation the average current flowing in the pipe was 42·8 amperes, with a maximum of 70 amperes. Under three-wire operation this current was reduced to an average of 6·3 amperes and a maximum of 20 amperes " ; and further on, " In these three cases the three-wire operation shows a reduction in current flowing in the pipe of 85, 85 and 88 per cent. respectively "

The lead sheaths of tramway feeder cables are obviously liable to electrolytic action and even fusion. American practice is to insulate the lead as much as possible and divide it into sections, while leadless cables are largely used in England. An attempt to earth and bond the lead of positive feeders is not to be commended, as it encourages heavy rushes of current along the lead whenever there is a momentary short-circuit on the system. Instances have occurred of several feet of lead being burned off such feeders by a short-circuit. No electrolytic trouble appears to have been recorded with single-phase traction lines, although the fall in potential along steel rails must be much greater with alternating currents—certainly twice as great for moderate frequencies.

Electrolysis on Lighting Systems.—Earthing and Bonding.

Electrolysis on three-wire lighting and power systems is of a rather different order from that occurring on traction systems. The most serious form of damage, which is often called electrolysis, but which is not, is the burning and fusion of lead sheathings and pipes.

On a well-laid and well-maintained system of mains, earth currents of any magnitude do not normally occur. But on any fair-sized network there must always be small leakage currents, chiefly from consumers' premises and over " ends." Any damage caused by these small currents may be made inappreciable by bonding and earthing the lead sheathing of the wires. Bonding ensures a much larger surface by which the current may enter or leave the lead, and thus greatly reduces the current-density.

Efficient earthing prevents current leaving the surface of the lead at all. These small leakages are nearly always from the negative side of the system, and hence all the anodic corrosion must take place on neighbouring and better earthed sheathings or pipes. But the lead of a negative leaky cable is itself frequently corroded ; for instance, where passing through cement or plaster, and the corrosion must be cathodic in these cases. It is probably a combination of chemical and electrolytic corrosion, the latter acting as a reducing agent. Lead that forms the cathode of an earth circuit generally has a distinctive blue appearance, which is probably due to the removal of the film

of oxide which exposed lead surfaces acquire. Lead covered wiring of buildings should undoubtedly be all bonded and earthed, since the whole installation is protected by fuses. The case is rather different, however, for street mains, where the danger is not so much electrolytic corrosion as fusing and burning. The method on which the mains are laid decides the course to be adopted. The initial difficulty is *efficient* earthing. The contact resistance of any earth plate which is carrying a current, and is an anode, rapidly rises, because it drives moisture away from it.

Whilst earth plates may lessen corrosion caused by minute currents, they cannot deal effectively with large currents. This is exemplified in the case of a fault occurring on a cable drawn into a galvanised iron pipe 50 ft. long and 2 in. external diameter, which caused the copper of the cable to be welded hard on to the pipe. About 18 in. away and running parallel was a lead water pipe. The P.D. between this and the galvanised-iron pipe was measured, and was 218 volts, yet the current passing was only 3 amperes! The soil was ordinary red garden loam. Permission may sometimes be obtained to bond the lead sheathings on to water pipes; this, of course, makes a capital earth, yet its expediency may be doubted. For suppose a network of lead-covered cables laid " solid," the lead being bonded together wherever possible and earthed at some point or points, the third wire being earthed at the station to a water pipe. On a fault occuring, the lead being in direct contact with the copper, a very large current will flow, which is likely to burn off bonds here and there, but, presuming everything holds up, it may shut down the station, or at any rate one section of the network. This is distinctly objectionable, as reliability of supply becomes of greater importance every year.

A very good earth also defeats its object in another way, by forcing such a heavy current to flow along the lead sheath, between the fault and the earthing point, as to cause a considerable fall of potential along the lead. This tends to make the current arc to earth at intermediate points. This large current may be prevented by disconnecting the third wire earth connection, or by inserting resistance in it. If this be done the immediate effect is to raise or lower the third wire

earth potential above or below earth some 200 volts or so. The result of doing this will be to start a number of third wire earths on any old network, chiefly on consumers' premises, and also nearly to double the potential between the opposite pole and earth. This will tend to cause additional faults, is contrary to the B.O.T. regulations, and may be dangerous to life. If a " solid " system is *perfect*—*i.e.*, with the lead everywhere insulated, there is obviously no object in earthing or bonding, for, supposing a fault to occur, there is no path for the current and no current can flow. But there are, with most methods of laying, weak places, generally at saddles and where the cables enter manholes, where the current will get to earth and burn holes in the lead if there is no metallic path provided. Bitumen also breaks down and allows current to flow, if the lead be " alive " for any length of time.

These weak places may be far distant from the actual fault, and this is the danger of continuous lead without earth connections. Sometimes every saddle provides a path for the current, and corrosion then takes place at every such point. If now the lead be broken at short intervals, say at every joint, the corrosion or burning is limited to the particular length of cable in which the fault occurs."

This incidentally illustrates one of the advantages of a draw-in system, as with it the faulty length of cable is readily pulled out, examined and renewed if necessary. Further, long lengths of lead cables, all with the lead electrically continuous and earthed, actually invite tramway currents to travel along them. If the lead is insulated and broken into sections, there is no temptation to such currents to use it In laying down a system of mains, with the view of preventing electrolysis and burning, a good method would appear to be to break the lead into sections, and thoroughly to insulate it. An attempt to do this is made on some British systems, but the more popular course is to bond and earth the lead ; the earthing is done at definite places, an attempt being made to insulate the lead by laying the cable " solid " everywhere except at these points. The system devised by the Howard Asphalt

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* In spite of these remarks, the authors wish to point out that bonding and earthing is the recognised treatment of lead cable sheaths, and experience has proved its value.

Troughing Co., of insulating the lead and earthing sections through a light fuse, seems quite sound. The fuse acts as an indicator of the state of the section. It will, however, be often impossible to insulate the lead of service cables right up to the cut outs ; but the service lead may be insulated from the main lead. A partial course is the worst, such as some cables bonded and some not, and partial or bad earths, such as earth plates generally provide.

The lead of lead-covered cables laid in metal pipes should be made as continuous as possible, and should be well earthed. An analogous case is that of two or more lead-covered cables in one duct, a fault occuring on one is sure to burn holes in the others if the lead of each cable is not thoroughly bonded to the rest. If it were possible to make a line of iron pipes electrically continuous by bonding at the joints or otherwise, they would thoroughly protect lead-covered cables drawn into them from electrolysis by tramway return currents.

Corrosion of Armoured Cables.

Armoured cables laid direct in the ground generally suffer more or less from electrolysis. Joints should be lead wiped and the armouring should be bonded on to the lead. However, with the most efficient bonding, a heavy fault current (to which such cables are peculiarly liable) will always cause some corrosion, owing to the resistance of the lead and armouring. Insulating joints undoubtedly limit the fault current, but will often increase the corrosion on the faulty section. Stoneware boxes have been used and boxes made of glass have been suggested. Wooden or ebonite bushes in the glands of an iron joint box should never be used ; they always get wet and act as partial conductors. Bonding and earthing are not an absolute preventative . when a fault occurs part of the current may readily prefer to travel through 3 in. or 4 in. of soil on to some large pipe rather than by a circuitous path to earth along the lead. Also, simultaneous faults on a positive and negative cable may easily cause a heavy earth current between the two cables, the current taking a short cut via some pipe rather than the path provided for it. Steel armouring apparently often protects the lead from corrosion. It is sometimes found in practice that the armouring is pitted and eaten away

along its whole length, but the only place where the lead is at
all attacked is where the armouring has absolutely disappeared.
In all cases *partial* measures are the least effective.   Thus,
earthenware or stoneware ducts are the very worst kind in
relation to electrolysis.   They act as partial insulators, rapidly
absorbing moisture and becoming in effect electrolytes when
only a slight difference of potential is applied.   Those with
metal joints are worst of all, as the joints act as partial earth
plates.   Cement joints, unless allowed to remain uncovered
to set for at least 12 hours cannot be made watertight, and they
also behave as electrolytes, and electrolytic corrosion may
occur at every such joint.   However high the resistance of a
shunt to a circuit may be, some proportion of the current will
flow through it, so that however well bonded and earthed a
network is, if there are alternative paths for the current, they
will be used, and, if these paths are electrolytic, corrosion will
occur at the anode.
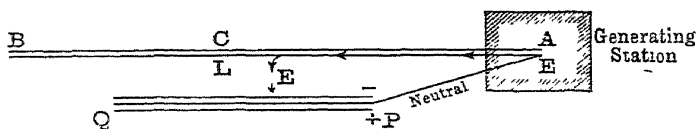
FIG 96.

In Fig. 96 A represents a station, AB a high-tension feeder to
an outlying district, C being the copper, L the lead.   PQ re-
presents the three wires of a three-wire system, supplying the
immediate neighbourhood of A.   On an earth occurring on the
negative of PQ, close to AB, the *direct* path for the current will
be from A along the lead of AB, *leaving* this lead close to the
fault, if the lead of the high-tension cable is bonded and earthed
at the station and the lead of the low-tension network is not
continuous.[*]

Precautions Against Electrolysis.

The problems most likely to arise are those connected with
old networks, which probably incorporate a variety of methods
of cable laying.   The proper course to pursue and the best

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[*] This case occurred in practice, causing a fault on the high tension
feeder

method of " nursing " such networks must vary in every case. An example of very extensive electrolysis occurring in practice may be quoted. A lead covered and braided cable, forming the positive main of a 460 volt three-wire system, was laid " solid " in an earthenware trough, in very wet heavy soil. It was surrounded by refined bitumen and supported on wooden saddles, which had been boiled in pitch and oil. After about two years' service, it was found that a length (about 50 yards) between two service joints (where the lead was discontinuous) was asunder. The leakage current was measured from both ends and the total was 0·25 ampere. On digging out this length, the cable was found to be almost completely destroyed. In some places, for continuous lengths of 3 ft. and more, not a vestige of metallic copper or lead was to be seen. These metals were replaced by a pale green salt (or salts) of copper (partly oxy-cloride), and a white salt of lead. A section showed these salts occupying exactly the relative positions and bulk of the metals in the sound cable, while the paper insulation was sodden, and in many places white in colour. The bitumen was generally good, but in patches it was brown in colour and friable. No action appeared to have occurred at the saddles. The troughing was cracked along its whole length, and was sodden with water. The cable had been well laid and was quite central in the trough, and not touching it anywhere. This example shows that bitumen and stoneware are not necessarily insulators. The continuous and uneven crack in the troughing was similar to those caused in concrete by electrolysis. It is probable that if this cable had had its lead *efficiently* earthed, most of this damage might have been avoided, but as the fault was one that probably broke down very slowly, it would have been " on " some time before being located, and hence have involved the risk of damaging the lead at some distant point. Actually the lead on either side of the insulating joints was quite sound. Had the cable been laid in an insulating duct with isolated lead, the fault would have been noticed during a periodical inspection of the manholes, as soon as the lead became " alive," and long before all this corrosion could have taken place.

A negative fault on a three-wire system nearly always damages the nearest gas or water pipe, the pipe being the anode

of the circuit. Nearly all the fall of potential occurs within 5 ft. or 6 ft. of the fault, since the fall of potential at any point near an ordinary fault in soil, plotted against distance follows a logarithmic law.*

To give some idea of the conductivity of the soil in towns, it may be mentioned that between two stations in Glasgow 1,580 yards apart the earth resistance was found to be about 0·05 ohm.†

Electrolysis in Mines.

In mines there is great difficulty in obtaining a satisfactory earth, and it is partly for this reason that leadless cables are largely used. Trolley rails are not electrically continuous and the specific resistance of sandstone and shale is of the order 500,000 ohms per cubic centimetre, whilst coal may be as much as 50 thousand million ohms per cubic centimetre. If continuous currents are used, the safest method, *as far as electrolysis is concerned*, would appear to be to use concentric cables, the outer conductor being bonded on to the lead and armouring at the generator. The lead and armouring must be continuous throughout. No serious difference of potential can exist between the lead and the outer, and any fault affecting the inner must cause a short-circuit, which will blow the enclosed fuses. The armouring and lead can, of course, be "earthed" as well as possible to comply with the rules. It should and can be made impossible for the inner conductor to become earthed at any part of the installation without melting a fuse, or bringing out a circuit-breaker. Whatever type of cable is used, the armouring is chiefly relied on for an "earth" in mines.

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* *See* Fig. 121, Part II., p. 349.

† Lackie. *Proc.* I.E.E., p. 128. Vol. XXXV.

CHAPTER IV.

ELECTRIC OSMOSE ON UNDERGROUND SYSTEMS.

If an electric current be passed through a solution, contain-
ing two electrodes separated by a porous partition, there will
in general be an increase in the volume of the liquid in the
cathode compartment, and a decrease in the anode compart-
ment, the liquid appearing to travel with the current. This
phenomenon is called electric endosmose, with reference to the
cathode. The total amount of liquid that will flow from one
side of the partition to the other depends on the strength of
the current, and on the time

$$V = Kit,$$

where i=current strength, t=time, K=constant, and V=
volume.

K depends on the nature of the solution, increasing with its
specific resistance. If the liquid cannot overflow, a reverse
hydrostatic pressure will be produced, which will eventually
balance the pressure due to the osmotic action. Its final
pressure P is directly proportional to the E.M.F. between the
faces of the partition. With a given current and a particular
quality of wall P varies as t/a, where t=thickness of wall,
a=area of wall face.

The observed effects of electric osmose are supposed to be
due to a natural potential difference existing between the liquid
and the partition, and situated at the surface of separation
The electric charges thus produced are acted on by the extern-
ally applied E.M.F., and result in the bodily passage of liquid
through the partition.*

If the particles of the partition were free to move, and the
liquid not free, they would tend to travel in the *opposite* direc-
tion to that which the liquid did formerly. This is the suggested

* *See* " The Theory of Solution," W. C. D. Whetham, Chapter XI.

explanation of the observed migration of particles of clay, and colloidal substances in water, to one electrode or the other. when an electric current flows. A similar action was shown by Prof. Forbes to the Royal Institution in 1895, in which a piece of cotton wick, projecting through a narrow opening in a glass bulb, in distilled water. was made to move in either direction, according to the direction of an electric current.

Thus whenever a continuous electric current flows through a solution contained in a porous body, as soil brickwork, earthenware. &c., or which is spread over an insulating surface, as a film of moisture on rubber or glass, then. in general, there will be an accumulation of moisture at the negative pole, and the neighbourhood of the positive pole will tend to become dry.

Prof. Haldane Gee[*] has shown how water is conveyed through blocks of concrete and plaster of Paris, and accumulates at the cathodes ; some of the blocks were broken in half, after the passage of a current. and the halves next the cathode were found to have a lower resistance than those next the anode. Electrical endosmose is said to cause the destruction of overhead line insulators on traction systems, since " water is drawn between the iron bolt and the insulating material and is forced through from the positive metal of the bolt to the negative metal of the hanger."[†] On any earthed system of continuous-current mains, electric osmotic effects are sure to be noticed.

The first recorded instance was on the St. Pancras mains, which were bare copper strip strained in culverts. Here metallic sodium and potassium were formed at leaky insulators, and a number of bad explosions occurred. The same effect is common with all three-wire culvert systems, and often with " negative " switches, fuse boxes, &c., mounted on damp walls. The insulator must first become leaky, and this may be caused by a film of condensed moisture and dirt on it, but often part of the insulator is short-circuited by spiders, spider's webs, or flies getting under the petticoat. If it be a " negative " insulator the leakage current will be maintained by electric endosmose, which will keep the surface wet. The

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* *Proc.* I.E.E., Vol. XLI., p. 455, *et seq.*
† *Proc.* I.E E., Vol. XLI., p. 485 (Cunliffe).

salts or metals formed are the result of the electrolysis of the water in the soil. If it be a " positive " insulator the leakage current will automatically cease, since there is no reservoir of water at the " positive " pole (the conductor) to keep the leakage surface wet. The " positive " conductors in a bare copper strip system always have a better insulation than the " negative," although a very high value can be maintained on the negative conductors too, if they are systematically tested, and all faults removed. Glazed stoneware insulators, supporting a negative conductor, sometimes become impregnated with salts, right through their substance, if the leakage has been going on for some time, and they have then to be renewed.

If the bare end of a wire connected to the negative side of a three-wire system be stuck into apparently dry ground, moisture collects around it almost immediately. The great trouble with 3-wire systems is to preserve the insulation of negative conductors, as, at exposed surfaces of porcelain, &c., there always tends to be set up leakage over the surface ; and with lead covered wiring, for instance, this is probably one of the main causes of failure.

As stated previously, there cannot be any electric osmotic effect on lead-covered cables (except at the ends), so long as the lead sheath is intact, but the question is one of great interest in connection with leadless cables Before any such effect can be exerted there must be a leakage current through the insulation. Now, with high class rubber insulation, the real leakage current *through* the insulation is practically nil, most of the observed current when testing, itself almost infinitesimal, being regarded as an absorption current, which gradually dies away.

Th is, before any electric osmotic effect can take place, the insulation resistance of the cable must fall ; this may perhaps be caused by the absorption of water, which does take place with rubber and vulcanised rubber to some extent. If it be supposed that what may be called the " normal absorption " of water by the rubber does not much affect the insulation resistance, the deleterious action of condensed water could perhaps be explained if the water " normally " absorbed held some substance in solution, because this solution in contact with pure water would exert an osmotic pressure and tend to

dilute itself by sucking in pure water, and thus an abnormal quantity of water might be absorbed.

Rubber is a colloid substance, and colloids "freely form addition products with such bodies as alcohol and water. . . The process of absorption of water is often accompanied by considerable increase of volume. . . . Many solid colloids and solid solutions of colloids and water can be used as solvents for mineral salts and acids . . . the ionic mobility and the diffusivity are then very little less than in liquid aqueous solutions of equivalent strength."[*]

Rubber does swell up to some extent when soaked in caustic alkali for a few weeks, and it seems probable that it does behave, perhaps, to a very limited extent, like the colloids referred to above, such as gelatine. This behaviour would explain the fall in insulation resistance, and, in the case of a "negative" cable, electric endosmose would, by forcing more water into the rubber, maintain the leakage current and cause the formation of the big blisters containing alkaline liquid sometimes observed.

"Positive" faults on rubber cables drawn into underground ducts are less numerous than "negative," and their presence on ordinary straight lengths of cable may perhaps be accounted for by the fact that the liquid conveyed by electric osmose is not always forced in the direction of the current, but in some cases its direction is determined by the nature of the solution, whether acid or alkaline. Thus it has been found[†] that proteid immersed in water reverses the direction of its motion, according as the liquid is made acid or alkaline; an acid reaction caused the particles to move with the electric current, which corresponds to the liquid moving against the current; with the liquid alkaline, the particles moved against the current, and hence the liquid would move with the current. Now a positive leakage current will produce, or tend to produce, an acid solution at the cable, and it is possible that this may reverse the direction of the electric osmotic flow of liquid, or at any rate largely neutralise it. So that instead of a "positive" cable tending to dry itself, as it will when the solution

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[*] W. C. D. Whetham, "Theory of Solution," Chapter XIV.

[†] *Transactions* American Electrochemical Society, Vol. X. (Carl Hering).

is alkaline (for example, the case of a thoroughly saturated " negative " cable changed to " positive ") it may actually tend to suck in water.

Rubber insulation becomes hard and almost visibly porous with age, and then rapidly fails if it becomes wet, but there must be some other cause in addition to age, as rubbler cables sometimes break down in a number of places after being only a few months in use.

Atkinson and Beaver,* speaking of vulcanised bitumen cables, say : " The results of these experiments show how certain agents not only have a surface action gradually thinning the insulating layer, but may by selective action be penetrating the mass. This latter effect would, of course, be enormously increased with cables carrying continuous currents and having earths on the circuits, on account of osmotic pressure forcing the chemical ions through the dielectric. Such action would be in some degree the equivalent of electrolytic action in lead-covered cables."

This statement obviously refers to electric osmose : on a three-wire continuous-current system there is always an earth on the circuits, the third wire being intentionally earthed. For electric osmose to come into action current must flow *through* the insulation, and this may occur normally or it may not occur until the insulation has been acted on in some way by water or other agent. When an " insulator " conducts, as they all will when heated, it conducts as a solid electrolyte ; therefore, if there is water in contact with a cable and a current passing across the boundary from water to cable, if electric osmose has any action at all, it must push water into the body of the insulator. In the ordinary way when electric osmotic effects occur there is a complete liquid electrolytic path. There is an interesting discussion on electric endosmose effects in Mr. Evershed's Paper, " The Characteristics of Insulation Resistance " † (Jour. I.E E., Vol. 52, p. 51).

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* Atkinson & Beaver, "Some Points on the Selection of Electric Cables." Paper read before the I E.E at Manchester, England, 1905.

† *See also* Papers by W. D. Bancroft, in Journal of the Am.I.E E.

CHAPTER V.

CAUSES OF FAULTS: MEASURES FOR PREVENTING THEM.

Speaking generally, cables used for alternating currents do not develop nearly so many faults as those used for continuous currents, and this in spite of the much higher pressures employed. Also, on a three-wire system, with earthed neutral, the negative cables break down sooner and to a greater extent than the positive cables. Moisture is to be avoided as much as possible, particularly on an earthed system and with leadless cables, and experience shows that it is much better for cables to be entirely submerged rather than merely wet. This is perhaps because the minute traces of chemicals that get deposited on the outside of the cable (as we think through electrolysis) rapidly diffuse away if there is any quantity of water present. Earthenware pipes, concrete, or brickwork tend to prevent diffusion, and thus cause an accumulation of salts on the surface of the cable. If it were practical, we believe it would be a good thing occasionally to flush out ducts containing leadless cables with clean water. Thus, in testing samples of vulcanised bitumen cables, with the insulation intentionally pared down to hasten the action, we have found the insulation to stand for long periods with 460 volts if the sample be immersed in a large volume of a neutral salt solution; but if it be put in a porous pot and packed in tightly with soil it will break down in a comparatively short time in the same solution.

Wishing to test samples of pitch and bitumen for use on a " solid " system, we installed bare conductors in stoneware troughs and filled in the troughing with the different samples, and connected the conductor to the negative pole of a three-wire system. In order to make the test as severe as possible, we wrapped another bare wire tightly round the outside of the troughing and connected this to the neutral pole, and then buried the whole arrangement. Under these conditions none

of the samples would break down, we think because the soil was altogether short-circuited ; by earthing the neutral a few feet away from the troughing we were able to break down some of the samples.

Leadless cables, particularly when in iron pipes, often break down close to the edge of the pipe. This is probably due to the fact that the protective action of the iron pipe, which is to make the path of any leakage current " non-electrolytic," is impaired, and a current may flow through the insulation along wet tapes or braiding to the earth, its path being electrolytic. Similarly, cables are sometimes found to be faulty at definite equal distances spaced along the cable, these distances corresponding to the joints in the earthenware pipes, which, if of cement, provide a better earth for the cable than the body of the pipe. Negative faults always collect an akaline liquid round them, and it should be the custom of the mains foreman to test any trickle of water running down a duct into a draw box with pole-finding paper for alkalinity, its presence always indicating a faulty negative cable in the duct. Faults on the positive and neutral wire (which is nearly always *above* earth potential) are generally acid, much drier, and with the conductor corroded.

The great object of the designer of joint boxes and other fittings for underground use is to exclude moisture, and faults caused by the ingress of water into joints, &c., should be regarded as due to faulty workmanship or material, and not as primarily due to water. No kind of fibrous substance, however well impregnated, can be regarded as waterproof.

There is one kind of fault the cause of which is difficult to classify : where bitumen cables are bent at all sharply the insulation will crack and open in time. Now service cables often have a nearly right-angled bend in them, and we have known many bitumen service cables to fail at this point.

Classification of Faults.

Faults on underground mains may be roughly divided into three classes :—

1. Faults of manufacture.
2. Faults caused during laying.
3. Faults caused after the cables are laid.

A fault may be either an "earth," a "short-circuit" or a discontinuity. With single cables it is almost impossible to get a short-circuit unaccompanied by an "earth," and with concentric or multi-core cables it is also very rare. Positive and neutral leadless cables are sometimes corroded asunder by electrolytic action, and may be clear of "earth," but this has always been caused by an "earth" originally. Multicore pilot cables sometimes develop a discontinuity without an earth, this being generally caused by a short-circuit which has cleared itself.

The faults coming under the first class are exceedingly rare, probably less than 0·1 per cent. of all those occurring on a low-tension network. Cables used for extra high-tension currents may possibly give a larger percentage. Proper testing of the cables will eliminate practically all danger due to manufacturing defects.

Perhaps 30 per cent. of all faults might be included in class 2, their chief cause being rough and careless handling of the cables. Negligent workmen will get sharp bends and kinks in a cable, will stretch the lead, drag the cable over sharp edges and rough surfaces, and in other ways lay up a store of future trouble. Badly aligned and inherently bad ducts and troughs, badly designed joint boxes and carelessly made joints are also responsible for faults caused whilst the cables are being laid. In very cold weather special care has to be taken in all the operations of handling and laying cables. The general remedy for this class of fault is, of course, efficient supervision. Really reliable foremen and gangers are difficult to get, and should be treasured when found. Faults of the second class may not, and generally do not, develop for some months, or possibly years after the cable is laid, and when they do manifest themselves the defect from which they originated is difficult to recognise. Thus the foreman responsible for laying the cable escapes all blame, and it is on account of the absence of any immediate result from improperly handling cables that it is so difficult to impress him with the necessity of using them tenderly.

Faults in class three may be caused by

    (*a*) Mechanical injuries.

    (*b*) Electrolysis and electric osmose

    (*c*) Chemical action.

    (*d*) Overloading and decentralisation.

    (*e*) Excess of temperature.

    (*f*) Abnormal pressures, surges, lightning.

    (*g*) Static discharges.

Faults due to Mechanical Injuries.

Faults in this category are most generally caused by workmen engaged in excavating the streets, for underground works, electrical or otherwise. Occasionally an iron spike used for supporting a barricade round some operation will be driven into buried cables. A particularly crude method used by gas engineers for finding leaks is responsible for some severe faults. This consists in driving a heavy steel bar a foot or two into the road bed on the supposed line of the gas main, and then applying the usual tests for the presence of gas. Unfortunately, the point of the bar may unwittingly perforate an electric cable.

Cables laid under concrete (as installed for wood setts) are very liable to injury if the concrete has ever to be broken up for installing other works, because wedges and steel bars are driven through it at random. Subsidence of the ground which is particularly common with cables laid in mines and mining districts, comes under this heading. This may cause joints to be pulled asunder or severance of the cable. In one instance, where cables were laid solid in troughing, the ground fell away from the troughs and carried them with it, leaving the cable taut, with the protecting bricks and a considerable weight of earth above it, which in the end cut through the insulation. The laying of ducts or troughs may also indirectly cause subsidence owing to their acting as drains for water.

Attacks by rodents also come into this class. We have found nests of young rats in manholes, but recorded instances of damage from this cause are very rare. An inspector, under the direction of the mains department and provided with a copy of all permits given for street openings of any kind, will largely obviate faults due to mechanical injuries.

Electrolysis and Electric Osmose.

Electrolytic damage is often underrated. It is discussed in relation to lead-covered cables in Part II., Chap. III, Although the term is generally applied to lead-covered cables. the slow deterioration of leadless cables possibly also is a kindred effect. Electric osmose is discussed in Part II., Chap. IV.

Chemical Action.

This is a relatively infrequent cause of trouble. Vulcanised bitumen is rapidly attacked by free alkalies, as described in Part II., Chap. I. Coal gas in the soil attacks and softens bitumen, and we have seen the bitumen filling of " solid " laid cables attacked in this way. Callender-Weber bituminous casings are sometimes corroded in a similar manner with holes eaten right through the wall of the casing. The slow deterioration of rubber in dry places, and its more rapid destruction by condensed water, may be included under this heading, although vulcanised rubber with no electrical pressure on it, retains its elasticity better in a damp box underground than in a dry one. Cement is also said to attack rubber chemically, but whilst agreeing that rubber cables should never be in contact with cement, we believe the action to be rather a consequence of the electric pressure across the rubber than a purely chemical attack. Most oils also slowly so ten rubber.

Lead is a rather chemically inert metal, that is, it does not readily enter into combination with other elements. For example, lead does not become converted into oxide by exposure to air in the same way that iron becomes rusty, nor does lead dissolve in sulphuric acid. This is due to the insolubility of the sulphate of lead which protects the lead from further action in the latter case, and in the former case the superficial coating of oxide which forms rapidly upon a freshly cast or cut lead surface protects the metal from further action and the oxidation of the lead does not progress. Hence lead has long been used for such purposes as roofing, water pipes, protection of cables, &c., where its durability is of the first importance.

Lead can be corroded and converted entirely into lead carbonate by exposure to the prolonged action of carbon dioxide in the presence of small quantities of organic acids such as acetic acid. This forms the basis of the Dutch process for the manufacture of white lead.

Now the lasting qualities of lead in the presence of sulphuric acid, as in the lead accumulator or the sulphuric acid chamber, are frequently modified by external circumstances, and the lead fails to stand up to its work. The lead becomes corroded into holes, and the lead plates or sheets crumble away.

Lead-covered cables in very numerous instances have been at work for upwards of 20 years, and the lead sheath is as perfect as the day it was laid, but occasionally lead-covered cables have become corroded, causing the sheath to allow water to reach the insulation, and then to develop a fault.

The corrosion upon lead-covered cables has in many cases a very definite appearance.

1 The corrosion may take the form of patches of various sizes filled with a white deposit of carbonate of lead.

2 It may take the form of patches filled with lead in a very brittle and spongy state, in which the lead cracks and falls away with every movement of the cable.

3. The corrosion may be accompanied by the conversion of the spongy lead into lead peroxide.

4. Trouble may be caused owing to lead assuming a crystalline and brittle state, and then cracking. This is not corrosion, but a change in the physical state of the lead due to the working conditions.

The failures of the lead sheath of cables can be divided into three principal groups, viz. :—

(*A*) Chemical corrosion.

(*B*) Electrolytic corrosion.

(*C*) Failure due to change in the physical condition of the lead : *e.g.*, crystallisation.

(*A*) Chemical corrosion, unaided by electrolysis, is extremely rare, but cases have been investigated where the balance of evidence has been in favour of purely chemical corrosion. In such cases the failures of the lead have been in cable systems buried in soil in which the conditions approximate to the " Stack " or Dutch process of white lead manufacture. In

these cases the ground is filled with decaying organic matter, such as plant remains, peat, humus, sewage, &c., which produce organic acids and carbondioxide, and the lead becomes covered with a coating of white lead (basic carbonate of lead) and occasionally the conversion has gone right through the lead to the insulation. It follows, therefore, that lead should not be laid unprotected in such ground, nor in ground which is under cultivation. Where it is necessary to lay lead-covered cable in such ground, external protection of some suitable description must be provided, or the cable must be laid embedded in pitch. The contact of damp wood (especially oak) with lead is particularly to be avoided.

(*B*) Electrolytic corrosion is by far the most common form of corrosion. This takes place in a variety of ways, and for a number of reasons.

The continued electrification of railways and tramways has resulted in the alteration of the underground electrical conditions, and stray currents are picked up and carried by any conductor available. If moist earth and a metal are available for carrying the stray current, the current will choose the best conducting medium. It frequently happens that the soil, in places, is a better conductor than the lead, hence the current will leave the lead in favour of the soil, and a corroded patch develops at the point where the current leaves the lead. The product of the corrosion which remains in the patch depends upon the chemical constituents of the soil. In other cases the lead becomes brittle and falls to a powdery mass, which is due apparently to the conversion of lead into an allotropic modification. It has been shown that when lead forms the electrodes of an electrolytic cell and dilute nitric acid is the electrolyte, the positive plate falls to powder, which is an allotropic modification of lead, and differs from ordinary massive lead in its physical properties, such as specific gravity, specific heat, &c.

As nitrates and nitric acid are found in soils, the conversion of lead into its allotrope may take place under the influence of electrolysis by stray currents. In some cases the spongy, powdery lead remains as such, in others the lead is converted into carbonate by the action of carbon dioxide from the soil. Corrosion of this description seems to be practically independent of the small quantities of impurities usually found in

commercial lead. The influence of impurities to the order of 0·02 per cent. requires further investigation. It is, however, interesting to learn that white lead manufacturers demand pure lead, not only on account of the colour of the white lead, but because the purer the lead the more rapidly it corrodes.

Further, lead occupies such a position in the electrochemical or voltaic series, that small quantities of other metals alloyed with it, would modify its electro-chemical properties. It is probable that the introduction of a very small percentage of copper would reduce the tendency to corrode under certain conditions. In support of this view, it is known that lead containing a minute percentage of copper lasts longer than pure lead when exposed to the action of sulphuric acid and oxides of nitrogen in lead chambers. The proportion must be kept to within very small limits or the lead could not be extruded from a lead press and the lead, even if extruded, would be too hard and brittle to allow of bending. Owing to the great changes in the electrical conditions underground, it is highly desirable that a preliminary electrical survey of the proposed cable route be made, prior to laying the cable, so as to provide the necessary earthing of the cable sheath, or protection from corroding. From an electro-chemical standpoint, the provision of adequate and efficient earth plates, which give a path by which the current can leave the lead, should form the best protection of a cable system, liable to the influence of stray currents.

In addition to the chemical and electrolytic corrosion, trouble is occasionally experienced owing to the cracking of the lead sheath. This occurs especially in positions where the lead is exposed to extreme vibration, such as cables suspended overhead, and subject to windage ; on cables connecting land ends of bridges ; or cables laid in loose ground, in which the cable is shaken by passing traffic. The cracking usually occurs at the junction of the moving and the fixed portions, and is caused by the gradual fatigue of the metal.

The microstructure of all metals undergoes profound variations under the stresses of mechanical work, the change in structure due to work increasing the mechanical strength up to a certain maximum. Beyond this point the metal experiences fatigue, the mechanical strength falls off and the metal becomes brittle and useless.

The mechanical properties of such fatigued metal can usually be restored by prolonged annealing at a suitable temperature. In the case of lead sheathing of cables the possibility of annealing is excluded, and where the cracking has occurred it is necessary to remove the defective portion, and suspend or relay the length, so as to remove the cause of the fatigue as far as possible, and prevent a recurrence of the trouble.

The appearance of this variety of trouble is characteristic. Usually there is no evidence of corrosion, the surface of the lead being clean and bright. Irregular cracks develop apparently along the interfaces of crystals, apparently cubes of varying size, and the surface and section show evidences of crystallisation. This crystallisation is limited to the affected position, the lead on either side of the cracks being usually perfect.

Crystallisation of lead is aided by increase of temperature, the trouble taking place more rapidly the higher the temperature, and lead which is unduly hard and exposed to vibration and movement crystallises rapidly

It is impossible in a limited space such as this, to do more than indicate the main troubles which are met with in lead sheathing. In many instances it is too late to investigate the cause of the trouble, the fault which developed having burnt out the evidence: nevertheless, the balance of evidence is in favour of the probability that the majority of cases of corrosion are electrolytic, and that with proper attention to laying a lead sheathed cable system should be the most permanent and reliable of all systems. A device has recently been patented by Mr. R. W. Blades and the British Insulated and Helsby Cables Co., which is designed to prevent the cracking of lead cable sheaths mentioned above. It consists (*see* Fig. 97) of a type of gland, which, if fixed at joint boxes, in conjunction with a Vernier expansion joint, enables the cable to move bodily (within limits) in relation to the joint box, in all directions, *i.e.*, laterally or radially at or near the point where it enters the box and some distance in advance of it, as well as longitudinally into and out of the box, at the same time preserving a compound-tight joint. It is claimed that this bodily movement will be allowed to take place actually within and in relation to the box and its fittings, and that the movement will not take place about any specially localised point of the cable.

FIG. 97.
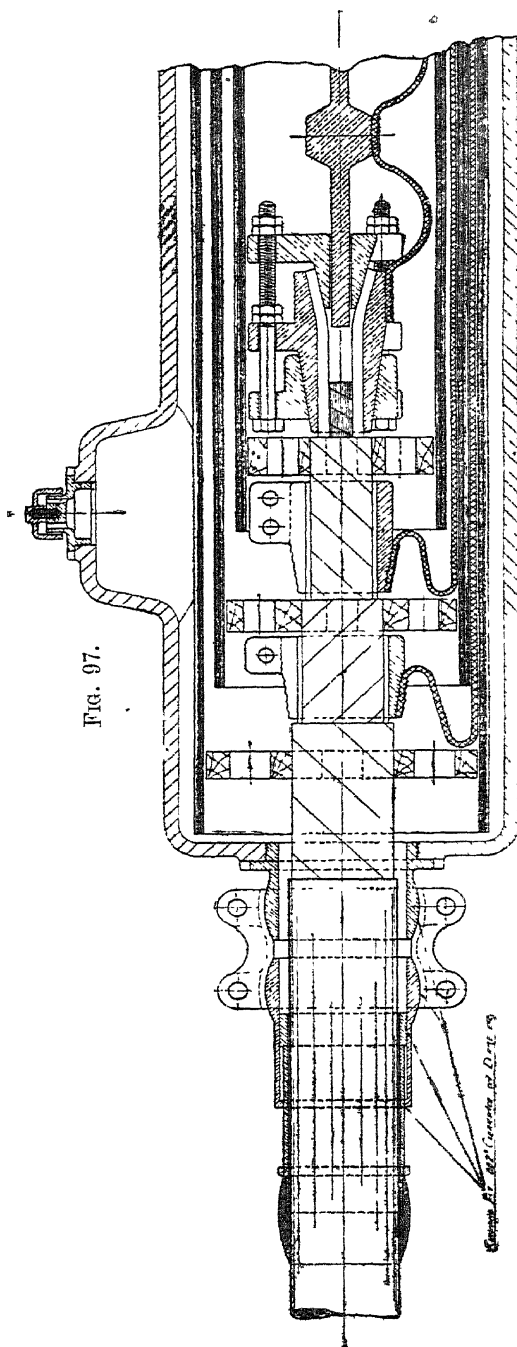
The construction of the gland by which the ends above referred to are accomplished is as follows : On the joint box is screwed a tubular fitting substantially larger internally than the cable, so that room for movement of the latter within the former is provided for. The outer end of this fitting is spherical—that is, externally, it forms a portion of a sphere. Beyond this device there is another tubular fitting of the same internal diameter, and similarly of external spherical formation, and separated from the former a certain distance ; and outside these two tubular parts there is provided a double internally spherical connecting piece, one spherical portion of which fits over and works on the first mentioned tubular fitting, and the other over and on the other spherical device.

The second tubular fitting is extended outwards and forms a cylinder or tube surrounding the lead sheathing

of the cable, but substantially larger; and within this cylinder a piston or collar formation on another tube, which is wiped to the lead sheathing at a point beyond these parts, fits and works; this tube being also somewhat larger internally than the cable sheathing. By this means provision for longitudinal movements of the lead sheathing within the box fitting at or near the point of connection with the cable and the box, is furnished. When the relative movement of the cable with the box or fitting due to vibration, or variable vibration of the cable and the box, takes place, the cable and all the parts above referred to—including that portion of the cable just beyond the wiped joint—except the spherical ended fitting screwed into the box, will move bodily ; this movement being enabled to take place by the spherical connection described.

Overloading and Decentralisation.

This source of faults is most frequent with vulcanised bitumen and allied cables. Lead-covered paper cables of sections up to 0·5 sq. in. may be run at a current-density of 1,200 amperes per square inch for long periods without danger. Vulcanised bitumen cables, of course, vary considerably in kind, but probably 800 amperes per square inch is the maximum safe current-density for a 0·5 sq. in. cable. Smaller sections may be run at a relatively higher current-density, for whilst the heat generated in a 0·2 sq. in. cable is twice that in a 0·1 sq. in. cable for similar current densities, the heat dissipating surface of the former is less than 1·5 times that of the latter.

Rubber insulation deteriorates more rapidly when heated up by overloads than when carrying normal currents. Vulcanised bitumen softens when heated, and the conductor tends to become decentralised. This statement is often made and nearly as often contradicted. We believe the effect takes place far more readily with some makes than with others, and not to so great an extent with the more modern cables as with the earlier ones. Some examples of decentralisation have been discussed earlier, and also the general question of the heating of underground cables.

Effect of Temperature.

This is an infrequent cause of faults. Cables laid and jointed in warm weather may contract and break their joints during

cold weather. This is, of course, very unlikely to happen when they are in constant use, owing to the heat produced in them by the load current. At week-ends, however, they may be so free from load that they will assume the temperature of the soil, and if this is low they may suffer severe strain, thereby causing distortion of the box fittings and bringing them into contact with earthed boxes and bonds. Some cases have been recorded of long feeders failing in this way. That there is a considerable strain may be seen by cutting a heavy feeder cable in cold weather, when the two cut ends will sometimes spring apart as far as 6 in. On the other hand, cables laid " solid " in cold weather must expand a little when they are used, and, being held everywhere rigid, must tend to break some of the joints of the troughing in which they are laid. Rubber and bitumen cables rapidly deteriorate when laid in proximity to bakers' ovens, buried steam pipes, &c., and they should be avoided as much as possible when laying cables, although this is sometimes difficult.

Abnormal Pressures and Lightning Discharges.

A lead-covered paper-insulated cable is hardly ever broken down by high-pressure rises occurring in practice, the failure generally taking place at joints or other fittings, transformers, &c. The general causes of pressure surges have been indicated in Chap. XI., Part I.

Lightning phenomena are not often manifested on wholly underground systems, but may be a great source of trouble on these when associated with overhead systems. We have, however, seen several cases of lightning charging underground mains. Cables used for a town supply come to the surface in a consumer's premises, and the whole system may get charged if a building is directly struck by lightning, but it is more probable that an electrostatic charge is induced by a heavily charged cloud immediately above. A conductor inside a conducting vessel is screened from all electrostatic influences, hence lead-covered or armoured cables, or any class buried fairly deeply in good conducting soil, are completely screened from induction by a cloud, but it would appear possible that non-lead-covered cables laid in insulating ducts above cellars,

with very little covering but the dry pavement flagstones, and bare copper strip strained in culverts, also with very little covering, and that nearly insulating, might be electrostatically charged. The subject is of great interest, but its occurrence too rare to discuss fully here *

Static Discharges.

Rubber cables have been known to fail when carrying high pressures when they are near some earthed metal. This is attributed to a kind of brush discharge which oxidises the rubber and destroys its insulating properties in course of time.

Practically all the causes mentioned above as the origin of faults must operate equally on all the three cables of a three-wire system, yet with leadless cables the negative cables develop at least 90 per cent. of all the faults ; with lead-covered cables the proportion is more equal between the positive and negative mains, and this is probably because the electric osmotic effect is largely eliminated. An interesting case was quoted in the " Electrical Engineer " (Feb. 1, 1907) of a gutta-percha cable that carried continuous and alternating currents, alternately, breaking down with the former but carrying the alternating current (with the same voltage) satisfactorily

Faults on Neutral Wire of Three-wire Systems.

Third wire faults are very rare if the third wire is always kept anchored down at earth potential ; they chiefly develop in the immediate neighbourhood of positive or negative faults. For instance, in the case of three single leadless cables laid in adjoining earthenware ducts, if the negative insulation fails, and if there is no earthed metal in the immediate vicinity, the leakage current will be some very small fraction of an ampere, but the soil and earthenware round the fault will be at nearly the same potential as the negative conductor. The third wire will thus be, at this point, say, 250 volts potential above the casing, and soil in which it is laid, and will thus tend to break down. The positive conductor will tend to be at nearly twice

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* For an account and discussion on " Lightning Arresters " *see* Leck *Proc.* I.E.E., Vol. XL., p. 493.

Its normal potential above the soil at this point. We have frequently seen a faulty negative bitumen cable replaced with a lead-covered cable, and after perhaps a few months this has failed also, and it has always been found that either the old positive or the third-wire bitumen cable had also failed near the original negative fault, and that current had in this way got on to the lead at this place and corroded it, probably also at several other points further away, where it was near a water-pipe or other earth.

The following table is due to Mr. C. E. Phelps, and gives the number of faults from all causes on the high and low tension and telephone cables in Baltimore during the seven year ending December, 1906, the total length of cable in operation being about 290 miles.

Nature of damage.	No. of faults.	Percenta_ of wh.a
Defective cable	3	2·0
Damage during installation	24	16·0
Mechanical injuries — Damage by picks, bars, &c	58	
Mechanical injuries — Floods	2	
Mechanical injuries — Gas explosions	2	55·0
Mechanical injuries — Rats	5	
Mechanical injuries — Workman in manholes	13	
Electrolytic action	31	20·0
Cables above ground	2	1·5
Unknown	8	5·5

This table exhibits generally the number of faults to be expected in a modern city from external and mechanical causes. It is no criterion of the number and importance of faults that are consequent on electrical defects, such as electric osmosis on three-wire systems. Half the mechanical faults occurred during two years when many street improvements were carried out after a fire, so that the percentage shown in the above table is not an exact guide for ordinary practice.

Manhole Explosions.

Manhole explosions are caused when an accumulation of inflammable gas is ignited by an arc on a faulty cable, or by sparking generally. It is possible that gas may be exploded by the hydrogen which takes fire when sodium or potassium combine

with water. It is well known that metallic sodium and potassium are deposited on a faulty negative cable by the electrolysis of the soil. The presence of these metals in a duct or manhole therefore implies a leaky cable or fitting, and hence this form of ignition is really only a special case of the general one quoted above. It is conceivable that a spark might be produced in a manhole by some stray current from an outside source, or from a fault current from somewhere else on the network, travelling along the lead of a cable. When a cable is used for high potential alternating currents the lead may spark to earth if it is not earthed properly, or if a bond has been melted or broken; this is a consequence of the condenser action of the cable.

The gas in the manhole may be the result of leakage from a faulty gas main, or it may be an inflammable gas generated by the decomposition of a cable dielectric or covering due to heating, or it may be an accumulation of marsh gas, CH_4, the miner's " fire damp." The latter is always a product of the decomposition of vegetable matter in soil, and hence may easily be present in underground ducts; it may also come from drains and sewers. The spontaneous combustion of phosphoretted hydrogen in air may be sufficient to ignite accumulations of other gases. PH_3 may be formed by the action of lime on animal phosphates existing in road refuse.[*] Coal gas is only explosive when mixed with air in certain proportions, the limits being 5 to 25 per cent. of coal gas. About 10 per cent. coal gas gives the most explosive mixture.

The gas given off by vulcanised bitumen, or the bitumen round a "solid" laid cable when heated, is probably a mixture of several hydrocarbons. The resin in a paper-insulated cable may also give off some explosive gas, such as olefiant gas (C_2H_4), but probably not to a sufficient extent in practice to cause an explosion, as a fault on a paper-insulated cable is generally very local, and only a small portion of the paper insulation is destroyed. Marsh gas mixed with about 10 times its volume of air forms a powerfully explosive mixture.

[*] We have records of two occasions, on which Electric Supply Engineers, have found a supposed leakage of electricity to be phosphoretted hydrogen burning on the road surface.

Bare copper strip in culverts has earned a bad reputation for explosions. The gas in this case must come from an outside source—*i.e.*, it must be coal gas or some gas generated from decomposing matter in the soil. This is the most likely case for the firing to be caused by sodium or potassium, as accumulations of alkali salts often appear in concrete culverts on the insulators ; these metals when combining with water might generate sufficient hydrogen to form an explosive mixture. If an arc is formed between two adjacent strips of copper of opposite polarity in a culvert it may travel along the copper for a considerable distance, travelling in such a direction so as to increase the area of the circuit of which it forms a part. Such an arc may then fire gas in a manhole some distance from the point where the arc was formed. Its path may be traced by the little beads of copper formed on the strip. A travelling arc may be prevented from going far by inserting dividing fillets of slate between the strips of opposite polarity in the straining boxes.

Vulcanised bitumen cables drawn into earthenware ducts are probably the most fruitful of explosions, and this is because this class of duct is the very worst for such cables, and hence faults are more frequent with this combination than with others, and where faults are frequent there is naturally a great probability of explosion. Also a vulcanised bitumen cable is likely to generate inflammable gases in greater bulk, and at a greater rate, when overheated than other types of cables. Some disastrous explosions have occurred in Manchester, within the last few years, which have been mostly attributed to the volatilisation of the bitumen surrounding the cables and the formation of an explosive mixture.

In a report by Mr. J. A. Bell to the Gas and Electric Lighting Committee of the Aberdeen Corporation,* on the culvert explosions in that city, it is stated that the mere sudden expansion of air, caused by a short-circuit will blow up manhole covers. " Those experiments tended to show that the explosions were in many cases brought about by the sudden heating and consequent expansion of the air in the manhole or culvert." On the other hand, violent short-circuits have occurred in manholes and culverts that have *not* blown up any

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* THE ELECTRICIAN, August 23, 1907.

covers, but as direct experiment has proved its possibility, the fear of its occurrence can never be entirely absent. Very curious things happen sometimes in connection with explosions on mains. Cases have occurred where, starting at some fault a series of some twenty manhole covers have been blown up one after another along a whole street. The ducts and man holes in these circumstances were probably all full of a fairly strong (over 15 per cent.) mixture of coal gas and air, and this burned back through the ducts causing an explosion in each manhole. Often the most unexpected cover will blow up. Referring to Fig. 98, A, B and C represent three manhole covers connected by ducts as shown ; a steel wedge was driven into a
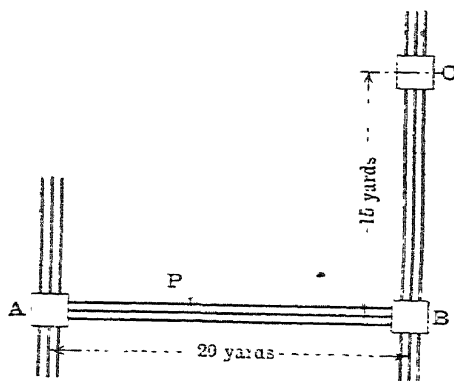
FIG. 98

cable at P, causing a bad " earth." The manhole at B was open at the time, A and C were both caulked down and air-tight. The cover of A was light compared to that of C which was exceptionally heavy. Before A could be opened, C cover was blown up at least 20 ft., although nothing was wrong with the cables in C. After A was opened, and the fault disconnected, some gas continued burning at the mouth of the ducts, leading from B in A. It was burning with a blue flame and came in gusts, with a roaring noise, very like a large blow lamp. The faulty cable was lead covered, and paper insulated, and about 2 in. of it only were burned away. This explosion may have been caused by marsh gas, and probably the large earth current travelling on the lead of the cable produced a spark in box C.

The boxes were carefully caulked down afterwards, but no trace of coal gas accumulating could be found after some weeks. It is said, however, that coal gas percolating through soil, may lose its characteristic odour. Stoneware conduits with square holes are sometimes shattered by an explosion if it takes place wholly or partly in the ducts. Occasionally they will be cleanly divided as if cut with a chisel (*see* Fig. 99) ; this has been found to occur on 10 or more consecutive casings each 2 ft. long. As regards remedies, ventilation may be used to prevent the slow accumulation of gases, and also to minimise the effect of the explosion, but will not be an *absolute* safeguard if the gas is there and a spark occurs.
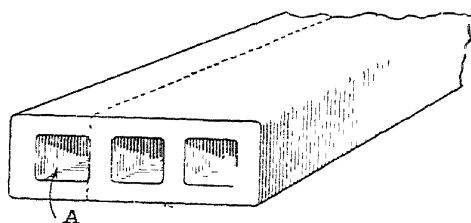
FIG. 99 —EARTHENWARE THREE-WAY DUCT

Dotted line shows course of fracture caused by explosion in duct A.

The best and easiest method of ventilation is to use ventilated box covers. Such covers must tend to promote a circulation of air along the ducts, since heavily loaded cables will heat up the air in them more than where the load is light. Also any gas, lighter than air, getting into the boxes, will escape. Fig. 100 is a sketch of a portion of such a ventilated water-tight box The cover and frame are of cast iron, the cover being filled with concrete, and hinged, so that in the event of an explosion, the danger is very much minimised, the cover flapping open and then shutting down again. Such a cover requires no caulking , the drain pipe may be led to the gutter, or be built round with broken stones. Box covers have also been chained down to minimise the effect of an explosion ; even should the chain break it is unlikely that the cover will rise high enough to *fall* on a passer-by, which is the worst danger. A brick built box, lined with cement is both

cheaper and handier than a cast-iron box. There is no difficulty in making it water-tight. When it is remembered that manholes have frequently to be built in between and amongst pipes, and with ducts coming in at all sorts of different angles and levels, the superior adaptability of the brick box will be evident. With a cast-iron manhole, it is sometimes necessary to find the place where it is possible to put it, rather than to put it in the best possible place.

Explosions other than those in street boxes are most frequently caused by vulcanised bitumen cables and sometimes
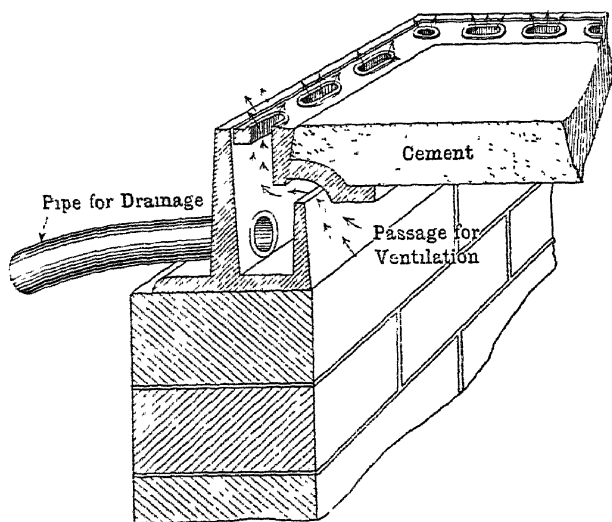
FIG. 100.—VENTILATED, DRAINED AND HINGED MANHOLE COVER.
The outlet of the drain is covered with broken stones. The cover bears at each corner
Hinges not shown.

by the bitumen used in laying cables on the solid system. Serious explosions have taken place in cellars due to the ignition of gas from a vulcanised bitumen cable or from bitumen filling. If pipes are used to convey the service cables into the cellar the gas has an obvious means of entry, but without pipes it may often be forced into cellars, if the pavement above is impervious. The Departmental Committee on Electric Mains Explosions in their report (*see* THE ELECTRICIAN, July 10, 1914) say : " All the bad cases have been

due to the use of simple vulcanised bitumen insulation and to the use of bitumen as casing or as solid filling." An appendix to the report quoted above, by Dr. R. V. Wheeler, gives an account of the gases evolved from bitumen and pitch at different temperatures. The following quotations are from this report : "If any combustible gas be heated to a sufficiently high temperature before being allowed to issue into the air it will ' spontaneously ' ignite "—" any mixture of air and the sample of bitumen gas tested, that contains between 5·4 and 20·5 per cent. of bitumen gas, is capable of self-propagation of flame ; whilst in the case of the gas evolved at 1,000°C. from the pitch and whinstone dust composition, the limits lie wider apart—any mixture of air and the gas containing between 10·7 and 47·5 per cent. of gas is capable of self-propagation of flame." "When the gases are ' cracked ' . . . . the percentage of hydrogen in them increases at the expense of the hydrocarbons. This tends to widen the limits of inflammability."

The gases evolved from (a) Callender bitumen, and (b) Glasgow pitch, at 1,000°C. without " cracking," have the following analyses :—

	(a)	(b)
Hydrogen sulphide ⎱ Carbon dioxide ⎰	3 95	2·7
Benzene ⎱ Ethylene hydrocarbons ⎰	12·75	0·75
Carbon monoxide	15·1	13 0
Hydrogen	37 4	70 0
Methane	18·0	8 15
Ethane	10 6	0 8
Nitrogen	2 2	4·6

" There is not much to choose between the materials as far as the volumes of inflammable gases evolved are concerned." " If ' cracking ' of the gases is presumed to take place the difference in composition between bitumen gas and pitch gas largely disappears, so that the limits of inflammability of the two kinds of gas become similar."

CHAPTER VI.

CABLE DUCKS AND TROUGHS.

Desirable Properties.

Ducts laid underground for the accommodation of cables should possess the following properties. They should be

1. Mechanically strong.
2. With joints unaffected by a subsidence of ground beneath them.
3. Water tight and gas tight.
4. Chemically inert.
5. Perfectly smooth on their interior surfaces.
6. Either electrically insulators or good conductors.
7. Reasonably cheap.
8. Non-absorbent.
9. Non-inflammable.
10. Not liable to become sticky with any rise of temperature
11. Quickly jointed and adaptable.

Earthenware Ducts.

The simplest variety is the ordinary drain pipe, into which three or more cables may be drawn, or three or more separate pipes may be laid, one for each cable, either side by side or in tiers, the joints being generally made with cement and the whole protected by a covering of concrete. The only hope of making the joints water-tight with cement is to leave the trench open for at least 12 hours after jointing to allow them to set, as ramming the ground above, if the joints are at all green, is sure to spoil them. A better joint is made as follows : The ends are previously painted with gas tar, and after the spigot end is inserted in the socket a single turn of yarn is put in and packed with a staving tool ; a mould is then made of clay round the joint and melted blast furnace pitch poured in. When this is cold it makes a very strong joint.

The yarn is to prevent the pitch getting inside the pipe.   If this occurs it will be detected at once by the smoke issuing from the pipe.

Composite ducts are made with round or square ways, from two up to six or eight in number.   One method of jointing these consists in placing an iron shoe underneath the two ends, which are butted together.   On the top, and meeting the sides of the iron shoe, a mould is placed, into which asphalt is poured. Prior to this, expanding mandrels are inserted in each way, and are withdrawn when the joint has cooled.   The ends of the ducts are specially prepared so that the compound may adhere well.   These joints give way when subjected to vibration or unequal pressure, owing to the ends being merely butted, and the conduit then acts as a field drain, conveying water from the surrounding soil into the draw boxes.

There are several other types of multiple-way ducts with spigot and socket ends, the joints being made with cement, pitch or tallow, or packed with a special composition ring.   In the Sykes type of conduit the lengths are supplied with the jointing material attached to the spigot and socket ends, an arrangement which renders them easy of manipulation.   To make the joint the compound is merely wiped over with tallow and resin before the two lengths are fitted together.   These conduits have the merits of cheapness, accurate manufacture, strength and self alignment.   The joints are quickly made by unskilled men, so that the trench may be filled in as soon as the conduits are laid.   The stoneware of which they are composed is very non-porous, and they are claimed to be watertight.   The jointing material is liable to be chipped off by much handling, and the dividing walls between ways do not make a good joint, so that two cables drawn into adjacent holes may be nearly in contact at some of the joints.   Probably this could be easily remedied.

Various devices are employed to get a true alignment of the ducts.   In one case, where the two ends are butted together iron dowel pins are used which fit into holes in each casing, five pins being employed for each joint of a four-way duct.   This joint is then wrapped round with prepared canvas, an arrangement which does not ensure permanent water and gas-tightness.

A number of single pipes laid side by side have this disadvantage :—when the soil is rammed above them the tendency is to force it between, and to separate them, and thus to spoil the joints. On the other hand, single pipes are more readily diverted to avoid obstacles. It is difficult to turn slightly a multiple-way conduit without leaving the joint open at one side, and the broader the conduit the more open will be the joint (*see* Fig. 101).

The labour of jointing is generally less with a multiple-way conduit than with separate pipes, but cables laid in the former are more liable to short-curcuit than if laid in the latter, particularly with metal joints.

Cables laid in stoneware or fireclay conduits are particularly liable to electrolytic action, and on this account it has been the
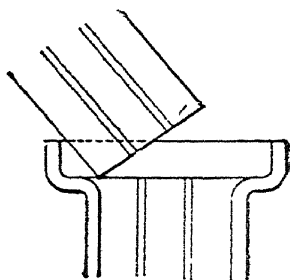
Fig. 101.—Showing Bend in Multiple-way Conduit.

custom of some engineers to use this type of duct for cables carrying alternating currents, but not for those carrying continuous currents. Single non-lead-covered cables appear to do worst in this type of duct, and one instance of this may be quoted :—

The pavement of a certain street was re-laid in sections, and on each occasion ducts for electric light cables were put in so as to avoid any disturbance later. In the first section three cast-iron pipes were laid, in the second a three-way earthenware casing, and in the third a bituminous casing. Eventually the cables drawn into these were of the vulcanised bitumen type ; but after about four years the insulation of the negative was found to be completely destroyed in the middle section,

although it was perfectly sound in the other lengths of cast-iron pipes and bitumen casing.

The joints of these ducts will rarely stand being undermined, and, whilst cement makes the strongest joint, it is unsatisfactory in other ways, and is also liable to crack the casing if it expands on setting, a result not infrequent with drain pipes. Another objection is that most vitrified ducts contain sharp projecting points which may cut grooves in the lead of a cable when it is being pulled in. The makers appear to be unaware of this defect, as even in sample ducts sent for inspection these sharp projections may be noticed. Apart from the troubles just outlined, earthenware casings are cheap, and there is no difficulty with cables sticking in them. Some kinds are strong enough, but the commoner sorts are easily broken.

Iron Pipes.

Cast-iron pipes are strong, and the joints are unaffected by undermining. If flaws exist, however, the pipes are easily fractured at these places. They are generally specified to be coated with Angus Smith's preservative compound. They resist corrosion well in most soils, but their high price prevents their extensive use. They can be supplied in long lengths, which entails comparatively few joints compared with earthenware casings, which are not made in longer lengths than 3 ft. Joints for the iron pipes are made with yarn and lead and are then caulked ; they can be made water-tight, but in long lengths of pipes there are often some bad joints. Cast-iron pipes are especially suitable for leadless cables, particularly if they can be kept dry, and if their electrical conductivity can be assured they will completely protect lead-covered cables from corrosion by tramway currents, with some precautions as to earthing. One of the chief objections to the use of iron pipes is that if a cable does fail it is liable to cause a very bad " earth " and to interrupt the supply. Another objection is that the expansion and contraction of fairly short lengths spoils the cement lining of draw boxes, and if these are in wet ground they will fill up with water. Wrought-iron pipes are cheaper, but rust away rapidly and are very susceptible to electrolysis, even when laid in concrete.

Composition Ducts.

Casings made of bituminous concrete are not easily damaged by a pick, owing to their toughness. They possess good insulating properties, but are difficult to make watertight. Early accounts of the Callender-Weber casing, which is of this class, all state that " General Weber has never been able to render the conduit entirely impervious to water" (Perrine). The joints are made by butting the ends together, inserting mandrels, and applying all round a hot compound, similar to the material of which the casings are made. The chief objection to these pipes is their liability to lose their shape under pressure, so that cables cannot be pulled out. Overheated cables also stick in them very tenaciously.

Bitumen casings have another drawback in being attacked and eaten into holes by the coal gas leaking from adjoining mains. This leakage of gas (which may amount to 10 per cent. of the output of the works) has a deleterious effect on all bituminous substances within reach, such as the casings mentioned above, or the compound employed for filling in cables on a " solid " system.*

Composition tubes made of wood fibre, or cellulose impregnated with wax and bitumen, form a very good insulating conduit, which can be made completely water-tight. They are of American manufacture. The joints for these tubes are made with screwed couplings, sleeves into which the pipes are driven, or spigot and socket ends. In any case the ends are painted with wax, and in the last method the joint is bound round with prepared tape and the pipes laid in concrete. If the sleeve type of joint is used, concrete is not necessary, but board, or other protection should be used to prevent injury from picks, &c. The paraffin wax used in the manufacture is said to act as a lubricant in pulling cables in and out. The permanence of these ducts underground has been questioned, but American experience is satisfactory in this respect. This is one of the most satisfactory insulating conduits hitherto introduced.

In very wet ground, these pipes (or any other kind) may be laid in wood troughs, and the whole filled in with pitch. This

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* Coal gas, is said, however, not to attack the insulation of vulcanised bitumen cables.

is a perfectly watertight construction, though of course expensive ; it combines the advantages of the " solid " and the " draw-in " systems. On a low-tension alternating system bare conductors could be used drawn into ducts laid in this way, and on a continuous current three-wire system the third wire could certainly be uninsulated.

Concrete ducts are largely used for telephone cables, and there has been proposed an ingenious system of forming concrete ways *in situ* by packing concrete round iron pipes used as cores, these being withdrawn when the concrete has set. The pipes, before being laid in position, are coated with some bituminous substance, and are then heated by passing steam through them until the bitumen is softened, when they can be withdrawn. This method has not been much used in practice. and concrete ducts have nothing but mechanical strength to recommend them.

Testing Ducts.

To test the watertightness and stability of joints. a trench lined with clay or cement may be made. and in this several lengths of pipe or casing are laid and jointed. the
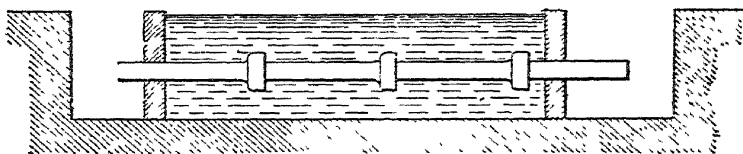
FIG. 102.—TESTING TRENCH FOR DUCTS.

ends projecting into a small pit at each end, the joints through the ends of the trench being made watertight with clay. After the joints have set the supports are taken away and the trench filled up with water (*see* Fig. 102). If no water gets in after a test of two or three days the conditions may be made more severe by putting a lead-covered cable into the duct and making the lead "alive" from the negative pole of a three-wire system. The composition fibre pipes mentioned above are the only ones the authors have found to withstand this last test.

A measure of the quality of stoneware or earthenware is the

amount of water it will take up. To test this, broken pieces should be thoroughly dried in a hot oven for 15 to 20 hours, and after being weighed should be immersed in water for 24 hours. After removal from the water they are rubbed dry with a cloth and again weighed. We have obtained values varying from 3 per cent. to 14 per cent. increase in weight for different samples under this test. An increase not greater than 2 per cent. is sometimes specified. Distilled water seems to give rather higher values than a strong solution of some salt, such as soda. Another method of testing the absorption of earthenware consists in observing the distance ink will penetrate a fractured surface.

Cable Troughs.

Troughs for laying cables on the " solid " system are made of iron, stoneware, wood, asphalt, concrete, and ferro-concrete. In considering any of the modifications of this system it should be remembered that bituminous substances are all viscous fluids, and even at normal temperatures tend to flow, although at a rate imperceptibly slow ; so that the containing troughs for bitumen should have close joints. Wood should be thoroughly impregnated with some preservative, such as creosote, under pressure, or it may be treated by an electric osmotic process to obtain the same result. The proper impregnation cannot be ensured by merely boiling it in some preservative. Creosote has an apparently similar action on bitumen to coal gas, making it permanently soft, an effect which may be observed with creosoted wood saddles.

Wood is said to last longest underground in wet clay, a shorter time in dry soil and a shorter time still in sand.*

Asphalt troughing, as made by the Howard Company, appears to be very suitable for a solid system, as it is easily laid and can be readily jointed with a hot iron, a steel sleeve being placed underneath the two ends to keep them closely aligned. Bends are easily made as required by heating a length of straight trough, and it has the immense advantage of requiring no saddles. It is made by rapidly rotating a cylinder containing the melted asphalt mixture. In this way the

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* *See* " Practical Notes on Electric Mains" (Lee).

heavier portions lodge on the outside, and the lighter and more fluid parts remain on the inside. The tube so formed is afterwards cut in two longitudinally and the two halves moulded to shape. When the cables are laid and filled in with bitumen a cover of asphalt is put on and ironed down. It is possible that this troughing might sink away from a well loaded cable in the event of any subsidence of ground beneath it ; wood troughing being generally nailed together in lengths would probably suffer least in such circumstances, and stoneware casings the most.

STONEWARE troughing can only be made in short lengths (up to 3 ft.), and the joints are a disadvantage , it is, however, very largely used.

IRON troughs may corrode in time, and are liable to cause a heavy earth in the event of a cable going wrong. They are particularly applicable to vulcanised bitumen cables. and this is probably the best way of laying this type of cable. Mr. G. L. Black,* speaking of lead-covered cables laid ' solid " in bitumen and cast-iron troughing at Glasgow, said " Unless an extra large size and correspondingly expensive troughing was used it was found impossible to prevent the lead from touching the troughing. This prevented proper filling, and was the cause of trouble through arcing."

FIBRE conduits, described above, have recently been adapted by the Key Engineering Co. for laying cables on the " solid " system. For this purpose a 90 deg. section is sawn out, which forms the cover for the troughing so formed. Saddles are used, made of the same material as the conduits. This makes a sound watertight job, but requires some additional protection from mechanical injury, and is relatively expensive for single cables.

Troughs are also made of FERRO-CONCRETE. which consists of a lattice work of steel set in concrete. The joints are of the spigot and socket type, and can be designed so that the steel is continuous at every joint. In a three-chase conduit of this material the socketed joints are screwed together. Covers are also provided so as to form a complete cage of steel round the cables. This affords a capital mechanical protection, but that

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* *Proc.* I.E.E., Glasgow, January 9, 1906.

it can protect the cables from electrolysis appears doubtful. If a good "solid" system is perfectly laid, there can be no necessity for an earth sheath except as a mechanical protection. If the cable is imperfectly laid, *i.e.*, touching the concrete at two points, the lead will form a shunt to the steel, and, should this be carrying current, one of these two points will be corroded, or both may be burnt. Of course the lead of the cable may be bonded to the steel to prevent this ; but if this is not done the semi-conducting path provided by the concrete, between the lead and the steel, produces precisely the condition it is desired to avoid. In any case the steel itself will be corroded and the concrete cracked if it has to carry any current.

A system has been tried with a three-chase ferro-concrete trough in each chase of which a bare conductor is supported on ring insulators of vitreous unglazed porcelain, threaded on to the conductor and held in place by special clips. The troughs are then filled up solid with insulating compound and covered with a suitable protector. Good results, for a time, have been obtained with this system in some places, but in others it has not been a success, probably owing to insufficient care in laying or unskilful manipulation. It is no easy matter to find the men who could be entrusted with the laying of such a system without constant supervision. Wet weather is a serious danger while the work is in progress, and subsidences of ground, or any cause tending to break the compound seal and admit water, will speedily prove fatal to the conductors.

It would appear that the iron sheathing of the troughing ought to be earthed frequently and well to prevent formation of caustic alkalies by electrolytic action, and the consequent destruction of the bituminous filling ; and this would be more effectively prevented if the sheathing were inside the trough— in fact, if cast-iron troughing were used instead of ferro-concrete.

These criticisms on ducts and troughing refer more particularly to continuous-current systems with the third wire earthed ; alternating-current cables give so little trouble that almost any variety is suitable, so long as it provides good mechanical protection.

Cable Supporting Saddles.

An important feature in a " solid " system is the choice of the supporting saddles, as it is there that some of its inherent troubles originate.

The saddles may be of wood, porcelain, metal or asphalt. Wood has proved a failure in many cases, as in the event of a lead-covered cable failing at any point the saddles provide a leakage path to earth, and over and over again the lead has been found corroded at every saddle. Porcelain is expensive, allows moisture to creep up between its surface and the bitumen, and also, unless it is very highly vitrified, it will absorb moisture like earthenware under the action of electric pressure. Metal saddles appear to have the disadvantage of directly earthing, or, worse still, partially earthing, the lead, which a solid system is presumably intended to insulate. On the other hand, they undoubtedly permit of the filling compound flowing completely under the cable. Asphalt saddles are certainly the best, but they should be made from carefully selected material, and not from refuse, and should be as hard as possible to prevent the cable from eventually sinking through them.

Covers for Troughs.

The cover of the trough may be of iron, concrete, tiles, bricks or wood. Whatever covering is used should overlap the sides, for it is found that when " solid " cables are damaged it is nearly always by a blow on the *side* of the trough. With overlapping covers, however, the troughs are difficult to pack properly with soil. Wood covers, impregnated with 10 lb. creosote per cubic foot, are good, as a pick will stick into them and warn a navvy that there is something there to be respected. Iron, also, by giving out a metallic sound when struck, is useful, while concrete and soft bricks are least effective. Hard blue Staffordshire dome-shaped tiles, 3 in. thick, are recommended. Recently a form of protection for armoured cables has been devised, which consists of slabs of concrete made in a mould, 2 in. thick, 6 in. wide, and of varying lengths.

CHAPTER VII.

CHOICE OF CABLES AND METHODS OF LAYING.

General Conditions.

The kind of cable selected and the method of installation will depend on the working conditions, and the choice will be governed by the following circumstances :—

1. Whether the installation is underground or overhead.
2. Effects of temperature and chemical action.
3. The relative potentials to earth and between conductors.
4. The system of supply of which the cable forms a part.
5. Whether the cable is to carry alternating or continuous currents.
6. Liability of the cable to overloading.

Generally speaking, lead-covered paper-insulated cables are the cheapest, vulcanised bitumen cables slightly more expensive, and rubber cables about double the price of either. Cables may be single, concentric, triple concentric, two or multi-core ; they may have various kinds of insulation, be lead-sheathed or non-lead-sheathed, armoured or unarmoured. They may be drawn into ducts or pipes, laid " solid," buried directly in the ground, or cleated to walls or other surfaces. Or bare conductors may be used, supported intermittently on insulators, either overhead or in culverts or subways underground.

Both on electrical and financial grounds, electric lines would probably always be installed overhead, if permission could be obtained. In the past, however, there has been considerable opposition to overhead construction in this country, and whilst in the future more overhead work is likely to be seen in rural districts, in town areas electric supply cables are certain to remain underground. For overhead work there is a choice between copper and aluminium, the question being almost

entirely one of price, though there are other factors such as weight, tensile strength, &c., which influence the decision. In some districts the conductors may have to be protected from corrosive fumes, and a cable sold as " indestructible " is claimed to be especially efficient in such cases.

Overhead conductors are subject to special troubles of their own from lightning and storms, while danger to the public is a possible objection in thickly populated districts. Hence, where continuity of supply is of great importance, and for high-tension lines, there are arguments for and against the use of overhead and underground transmission, apart from the question of cost. The upkeep of overhead lines is a not inconsiderable item, whereas the maintenance of a high-tension feeder laid " solid " ought to be practically negligible. Alternating-current feeders working at 2,000 volts have been in use for 15 years or longer without a single maintenance item being recorded against them.

Cables for Extra High Tensions.

The difficulty in designing E.H.T. cables is due to the disruptive action of the high pressures employed ; this is a consideration entirely absent with cables for lower pressures, which have a very large factor of safety against disruptive action. Rubber breaks down at between 12,000 and 15,000 volts per millimetre, and impregnated paper at an average of 20,000 volts per millimetre. The insulation of a cable cannot be indefinitely increased, because it becomes impossible to coil or handle, and also because of manufacturing difficulties an cost. Concentric cables thus become practically impossible for very high-tension work, the limit being fixed by the Verband Deutscher Elektrotechniker at 3,000 volts, although concentric cables are used for much higher pressures than this.

A cable used at Toulon for six momths by M. de Marchena for 28,000 volts had three cores, each of 25 sq. mm. section, made up of 19 wires and covered with 7 mm. of impregnated paper, the whole lead covered and of an external diameter equal to 65 mm. It was tested with 60,000 volts for one hour, 80,000 volts for one minute between conductors, and with

36 000 volts for one hour and 50,000 volts for one minute between conductors and lead.* The County of Durham Company have 20,000-volt cables working on their three-phase system. The cables consist of three conductors each of 32·5 sq. mm. section, paper insulation 13 mm. thick, and are lead covered and laid solid underground. They were tested with 100,000 volts for three minutes, 50,000 volts for one hour and 30,000 volts for 24 hours, and, after a bending test, with 80,000 volts for three minutes.

The maximum practical outside diameter of a cable appears to be about 90 mm. On account of this mechanical feature, and the greater rise in temperature with three-core cables, and also because of greater facility in grading the dielectric, single cables have been suggested as the most suitable for very high pres ures. Single cables are also more easily jointed and the dielectric losses are less.

Such cab es wi l always be lead covered and the dielectric probably composi e—graded.

Several engineers have suggested that metallic sheaths might be embedded in the insulation of a cable, these sheaths being connected to tappings from the transformer supplying the cable, thus equalising the potential gradient. Mr. O'Gorman (" Electrical Engineering," December 5, 1907) regards such sheaths as valuable, on account of their heat conductivity minimising the effects of local over-stresses in the dielectric. The Board of Trade may insist on an earthed sheath in an extra high-tension cable to prevent the possibility of anything external to the cable becoming charged and to increase the leakage conductance.

E.H.T. cables will have the maximum protection from external influences, such as electrolysis and chemical action, if laid so id ; on the other hand, if pulled into ducts, they will be far more quickly renewed if anything should go wrong, and, of course, additional cables can be added at a minimum of expense. If laid solid they are likely to be more gently handled durin g installation than when drawn in.

Mr. H. G. Stott recommends that high-tension three-phase

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* THE ELECTRICIAN, August 24, 1906.

cables have their lead sheaths insulated, the different sheaths be'ng bonded together and earthed at the generating station; also that, in manholes where more than one cable passes through, the cables should be wrapped w.th asbestos. A possible difficulty with graded insulation wo ild be the question of jointing but probably this would only mean des'gning the i)int boxes sufficiently large. The high-tension continuous-current transmission lines in use on the Continent, designed by M. Thury, are practically all overhead lines, except the Moutiers-Lyons.

Underground cables have been s 'ggested for such systems by Mr. J. S. Highfield,* and h describes some experiments to show that the disruptive effect of alternating pressures is much greater than that of continuous pressures of the sam *maximum* value. For the same *effective* values the disruptive effect of the alternating pressure will, anyhow, be about 1·4 times as great as the cont.nuous pressure. In the discussion on Mr. Highfield's Paper. Dr. A. Russell stated that the experience of several manufacturers was that their high-tension cables would stand continuous pressures at least twice as gre .t as the effective value of alternating voltages † It is. however. apparently poss ble to design a cable so that it should break down with a continuous pressure that it would be able to withstand i. alternating. Thus, if a particular layer of dielectric had, in comparison with other layers, a low resistance and a low specific inductive capacity, the fall of potential or electric stress across it would be (comparatively) low with a continuous pressure and high with an alternating pressure. If either kind of pressure exceeded the resistance to disruptive breakdown of the particular thickness of material employed, then this layer would fail.

Lead-covered cables are the best for underground use on earthed systems, for, even if there is a leakage current through the insulation, any lectrolytic effects it may produce will be

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* *Proc.* I E E , Vol XXXVIII , p. 471. Mr. Highfield now has cables in use in London on this system, working at 100.000 volts.

† For a full discussion of this question *see* a Paper by Dr. A. Russell, *Proc.* I.E.E , Vol XL , p. 6.

confined to the outs'de of the'ead sheath, and cannot spo l the insu'ation. Also, since lead is impervious to water, the electric osmotic effect is minimised.

High-tension Cables.

For single-phase alternating-current feeders concentric cables are used, primarily because the symmetrical arrangement of the conductors reduces the mutual induction of the cables to a minimum ; on similar grounds a three-phase cable is made up of three insulated conductors twisted together, which practically prevents inductive effects.

The paper-insulated lead-covered type has become the general standard in this country, although a good deal of rubber insulation, lead covered, is used in America. Rubber has this advantage over paper, that if the lead sheath is pierced at some point the rubber insulation may last an indefinite time without breaking down, whereas paper exposed to the air is certain to break down very rapidly. High-tension cables have been successfully used armoured and laid direct in the ground, laid solid, and drawn into ducts. Cables carrying high-tension currents are always important, the continuity of supply to a whole district perhaps depending on one cable. If there are no exceptional circumstances, and if good ducts are used, carefully laid. the drawn-in system is probably the best, owing to the rapidity with which renewals may be made. Single-phase alternating current concentric feeders for medium pressures, 2,000 to 5,000 volts, laid underground, generally give less trouble than any other class of cable. On a single-phase system the outer conductor of the high-pressure feeders is generally earthed. Thus any puncture of the lead will affect the outer earthed conductor first, and, if the cables are periodically tested the fault can often be located and removed before the moisture works through to the inner conductor, causing a breakdown.

Low-tension Cables.—Three-wire Systems.

Continuous-current three-wire systems are working under more onerous conditions, as regards maintenance, than any

other. This is due in great measure to the earthing of the third wire. For such systems practically every kind of cable has been used, installed in every possible way. Rubber-insulated cables were largely used in the early days, but these have almost entirely had to be renewed, even for alternating-current work. On two networks, within the authors' knowledge, the rubber cables were replaced by vulcanised bitumen, and these have in turn been displace by paper-insulated lead-sheathed cables. On the other hand, lead-sheathed cables have been discarded in favour of bitumen on some networks.

The number of faults on house wiring in any town are extraordinarily few, considering the many miles of rubber wires there are in use, often of very inferior quality. This is largely due to the fact of the cables being kept dry. Often there is no tendency for condensation to take place, and. where there is, the pipes are usually so filled up with wires that there is no room for moisture-laden air.

The close packing of cables into a metal pipe helps in another way—by making a good electrical connection between the surface of the insulation and the pipe. This has somewhat the same effect as a lead sheath, by preventing any leakage current through the rubber from depositing the products of electrolysis at the surface of the insulation. Rubber cables laid underground are generally exposed to wet, are heavily braided and have plenty of room. An electrolytic path is thus provided between the rubber and the pipe, which we believe to be the chief cause of breakdown In support of this view, it may be stated that cables which have behaved satisfactorily with alternating pressure for years have broken down in a few days when used for continuous currents of a lower maximum pressure than the alternating pressure.

Perhaps the most successful drawn-in leadless cables are triple-concentric paper-insulated with a vulcanised bitumen sheathing. The outermost conductor is made the middle wire of the system, and thus there is hardly any difference of potential across the bitumen sheathing, and hence no tendency to breakdown. The middle wire on most networks is a few volts positive to earth, and when the middle wire insulation does

break down the fault resembles a positive one. It thus makes a slightly sounder job to lay this type of cable solid, rather than to draw it into ducts.

There is a great difference of opinion regarding the use of lead-covered or leadless cables on three-wire networks. Undoubtedly lead-sheathed cables badly installed will give endless trouble, due to electrolysis and burning by their own leakage currents : but if properly installed they will give absolutely no trouble. To ensure success, minute attention must be paid to every detail, and, above all, competent jointers must be employed. We believe it would prove more economical in the long run to pay an experienced jointer £5 per week rather than to employ the ordinary promoted labourer at 30s. per week. It has been said by a mains engineer of great experience that he would prefer to maintain the worst possible cables installed and jointed by good men than good cables installed by inexperienced men.

Perhaps the best system, from a purely electrical point of view, consists of triple concentric lead-sheathed cables laid solid and protected by tiles. All the joints are lead wiped, and are (both straight and tee) made with concentric fittings, insulated with tape and covered with a lead box cast in two halves, which is wiped on to the lead of the cables and filled with wax from two holes in the top, which are afterwards sealed. Where the cables enter disconnecting boxes the lead is wiped on to glands screwed into the boxes. The ends of the service cables (concentric) are sealed in a trough where they enter the house-fuse boxes. Such a system, systematically carried out, is absolutely watertight. The lead is everywhere electrically continuous, and it has proved in practice to be entirely free from faults or trouble of any kind.

The feeders should, however, be single cables, as it is probably better not to fuse them, and an accidental blow from a pick on a concentric feeder might not only put a district in darkness, but even a whole town ; whereas damage to a single cable will make an earth, and not a short-circuit, and the cable can remain in use until a convenient time arrives for disconnecting and repairing it.

Single cables are also more economical for feeders on account

of the higher current densities at which they can be worked without prejudicial overheating, and are thus to be preferred to triple-concentric or three-core cables for lighting loads.

Drawn-in *versus* Solid Systems.

A drawn-in system has certain advantages over solid systems:

1. Although networks for residential districts may often be successfully calculated, yet in manufactuiing and " mixed " districts it is often impossible correctly to estimate the demand. Errors in design may be corrected with a drawn-in system at a minimum of cost and without any fresh opening of the roads.

2. The cost of a drawn-in system is less than that of a solid system, because, although the first cost of a set of cables drawn into ducts is slightly greater than the cost of an equivalent set laid solid, yet the latter must be big enough for their final possible load, and thus there is for many years a good deal of copper buried in the ground earning nothing. The cables on the drawn-in system need only be big enough for immediate requirements, and they can be drawn out and replaced by larger ones when necessary, the old cables being used elsewhere. If much cut up by service connections, the value of the copper can at least be realised; but if there are many services a second cable would probably be drawn in alongside the old one. The additional load can sometimes be dealt with more economically and conveniently by laying new feeders instead of altering the distributors, but this applies to short feeders only, and one of the great advantages of the drawn-in system is the ease and cheapness with which service joints can be made and unmade (*see* No. 5).

3. Faults are much more quickly repaired on a drawn-in system, it being only necessary to locate the fault to a street, and not to an exact point, as with solid or buried mains. The expense and delay in opening the ground are also avoided.

4. The natural and most economic feeding points for a town frequently shift, owing to new buildings, the migration of people from one part of a town to another, this generally being from the centre outwards, and the pulling down of old properties and erection of new buildings on their sites. With a drawn-in system feeders are very readily altered or extended,

so as to utilise their copper to the best advantage. A very convenient and good arrangement to employ, where a feeder has to be extended in existing network ducts, is to use a set of concentric cables, the inner conductor being of a larger section than the outer, and being made the feeder, the outer conductor being used as the distributor of the same polarity as the feeder. In taking connections off the distributor the insulation between the inner and outer conductors is thus never cut (*see* Fig. 103).

5. Service joints, being suspended in air in brick chambers, are very quickly and cheaply made without boxes, and the polarity readily changed for balancing purposes.

6. The existence of ducts in a street makes the change from gas to electric street lighting much cheaper than it otherwise would be, for the ducts can be utilised for lamp leads. There

Lead
Insulation
Positive Distributor
Positive Feeder
Neutral Wire
Positive Wires
Negative Wires
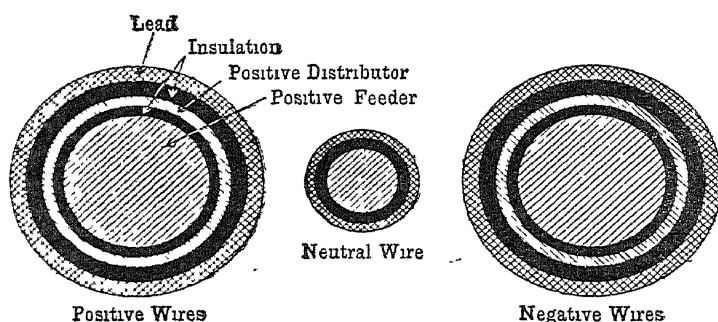
FIG. 103.—DIAGRAM SHOWING SECTION OF SET OF CONCENTRIC FEEDERS AND DISTRIBUTORS.

is no difficulty in drawing in or withdrawing three or four small cables in a duct only $2\frac{1}{2}$ in. square. This of course applies to either arc lamps which are run always in series, or to a number of incandescent lamps switched from one point. This latter method—running a number of incandescent lights on special leads and switching from one point—is certainly cheaper than making a special tapping off the distributors for each lamp and supplying a special switch for each. It also allows automatic switches to be employed, which are generally prohibitive if they have to be supplied for each lamp.

7. The possible depreciation of the mains is much less with a drawn-in system than with a solid system, for if the latter should break down the whole cost of the mains is lost, all the

trench work and re-instatement of roads has to be done over again, and the protecting material has all to be renewed.   In dealing with a drawn-in system the only renewable part is the actual cable itself.   If the copper and lead be recovered and sold, then the only part that can depreciate is the insulation, the cost of manufacture and the labour of pulling in and joint-ing.   This represents for an ordinary three-wire network only about 30 per cent. of the whole cost.   If the mains be laid solid, about 70 per cent. of the whole can depreciate * (*see* Fig. 104).
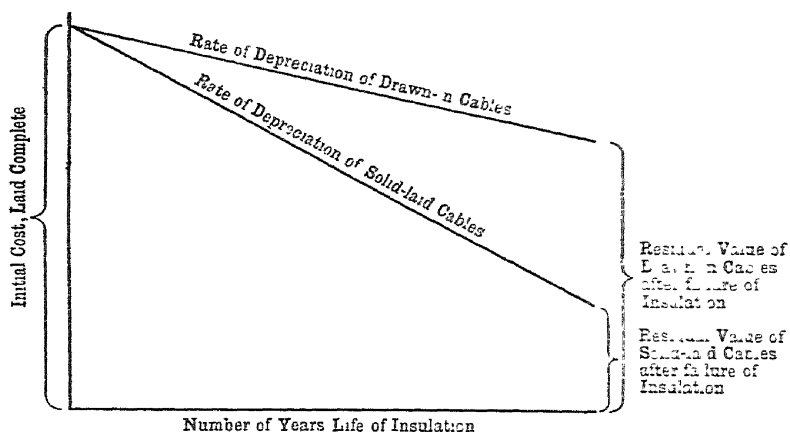
FIG. 104 —RELATIVE DEPRECIATION OF BURIED AND DRAWN-IN CABLES.

If the cables are to be drawn in, single cables are cheaper and more convenient than triple concentric or three core, chiefly on account of the much greater facility in making (and unmaking) service joints.   The essential idea of a drawn-in system is that the cables can be readily pulled in and out.   The joints on single cables can be made without either joint boxes or lead-wiped sleeves.   The disconnecting links being, like the joints, supported in air, can be uninsulated or merely protected by earthenware pots.

Three-core, lead-covered and armoured cables laid direct are rightly regarded with favour, especially for suburban and residential districts, in which the load is light and fairly deter-minate, and where low service costs are essential.   Although, perhaps, not so safe against the occurrence of faults as a triple-

* " Electrical Review," April 5, 1907.

concentric cable with earthed outer, the cheapness and facility of jointing are noteworthy features. The absence of fittings in the box and the simple nature of the joint make the total cost only about half that of a triple concentric box. This comparison is based on those of the cast-iron type ; with cast lead the difference is not so great. Service boxes for three single mains cost about as much as those for triple concentric.

Armoured cables laid direct in the ground and covered with a board constitute the cheapest system to install as regards first cost, though, like the solid system, the cables must be put in of a bigger section than is necessary for immediate requirements.

If the cost of a network in a district of heavy demand were considered over a period of 10 or 20 years, it would probably be found that a drawn-in system was cheaper than armoured cables buried direct in the ground. Concentric armoured cables make the cheapest form of service cable and are readily jointed on to single cables in a service pit, without the use of joint boxes.

Experience varies with armoured cables. Trouble has been experienced on some networks, chiefly owing to electrolysis, and in some cases to the use of iron joint boxes. Lead joint boxes are always preferable.

Culvert Systems.

Culverts containing bare copper strip, strained on insulators, are expensive to install, but make a capital job when well done. Service connections should not be taken off culverts. It is largely owing to the use of culverts for distributors that the system has been abandoned in some towns. One of the chief advantages lies in the fact that the conductors represent copper in its most portable form, and the section of the feeders can be altered so as always to be run at the best current density. A culvert feeder is essentially the mechanical engineer's solution of the problem of the transmission of electrical energy. Owing to the bad name they have got through explosions and to the high initial cost, and their great bulk, culvert systems are not now laid down or extended. In England, supply cables have been largely laid solid; in America they are generally drawn in ; and in Germany armoured cables laid direct in the ground or buried in sand are employed. The " solid " system has

been now almost completely abandoned, modern armoured cables being so heavily protected and impregnated with compound as to form the equivalent of " solid " laid cables. The manifold advantages of " drawn-in " systems, particularly in the streets of towns and cities, are also becoming more generally recognised.

Traction Cables.

Feeders for continuous-current 500-volt traction systems are both laid solid and drawn into ducts. The line side of the system is always positive—that is, above earth potential. Thus the insulation of the cables will be helped by electric osmotic action and tend to expel moisture. On the other hand the overhead line would be better negative, from the point of view of avoiding corrosion of the conductor. Both vulcanised bitumen and lead-covered cables have been used successfully. We should prefer to lay the cables solid, since there is not so much to be said for a drawn-in method here ; the loads are usually definite, and thus one would choose whichever class of cable was the cheapest.

If the failure of a vulcanised bitumen cable is due primarily to the action of water on the insulation, and secondly to the action of the leakage current caused by the fall in insulation resistance due to the water, then if the cable is normally maintained at a potential above " earth," the higher this potential is (within the limits of disruptive action) the less chance there would be of the cable failing, because the higher the potential the greater would be the tendency for electric osmotic force to keep water out of the insulation.

On the other hand, if the cable were maintained at a potential below " earth," the higher the potential the greater would be the chance of the insulation failing, because of the increased tendency to suck water into the insulation. It is possible that the success of vulcanised bitumen cables on tramway systems, under conditions where they have failed on lighting systems, may be due to the above cause—that is, because they are " positive " and because of the higher voltage.

Mining Cables.

Much trouble has been experienced with cables in mines. It is claimed that this class of work is the severest test to

which a cable can be put, and no doubt this is true as regards exposure to mechanical injury and general rough usage ; but since, with continuous-current supplies, the system is generally an insulated two-wire one, it is not, from an electrical point of view, so severe as an ordinary 500-volt three-wire town supply. Many mines are supplied with alternating three-phase currents, and these are never so difficult to deal with as continuous currents, from the maintenance point of view. In some mines it is very difficult to get an " earth " at all, and this must be in favour of the cable insulation, though objectionable from other points of view.

It would be impossible to say that any one class of cable is the most suitable for all mines, as the conditions are so variable. Water is usually present, and this would imply the use of lead-sheathed cables, if they could be adequately protected from mechanical injury. Once, however, a lead-covered cable did get damaged, it would be likely to cause far more extensive trouble than either vulcanised bitumen or rubber-insulated cables. Acid water is likely to attack the insulation, steel armouring and lead, while the corrosion of the latter is likely to be assisted by water containing nitrates, nitrites and chlorides and organic acids. Vulcanised bitumen is not dissolved by most acid pit waters, and perhaps does better in slightly acid rather than in neutral water. The cables in a mine have to be installed in three main positions : (1) The shaft, (2) the roads, (3) at the seam face as trailing cables.

The shaft cables are often duplicated to avoid total stoppage of the supply, two light cables being run connected in parallel instead of one heavy cable. This rather presupposes a break-down, but, owing to the difficult conditions, is probably a wise precaution. Trouble with water and injury from falling stones or coal are the chief dangers.

The oil in lead-covered cables has been known to flow to the lower part of the cable and to burst, by its hydraulic pressure, the lead covering or joint boxes there. This can be avoided by using paper impregnated with a fairly hard compound.

Pit-shaft cables are nearly always double wire armoured, and unless the water present is known to attack lead, probably

lead-sheathed cables are the best, at any rate for continuous currents. Alternating currents are always preferable, on account of reduced difficulties with the insulation and the absence of commutators on the motors. With alternating three-phase currents one or two three-core cables are likely to be used, the duplication being desirable on account of the reduction in weight of the individual cables, and also the greater security of the supply If bitumen cables are used, they should be all bitumen—that is, each core separately insulated with bitumen, twisted round a central core of bitumen. and the whole encased in bitumen. A three-core cable, in which the three insulated conductors are twisted round a fibrous core and the whole covered with fibrous material. is probably one of the worst types of cable for wet situations. Vulcanised bitumen cables, in which the interstices in the core are filled up with bitumen compound, prevent water spreading along a cable, but in no way reduce the number of primary faults occurring. We believe cables were first made in this way by Messrs. Callender for the Edinburgh Corporation.

Opinion generally would appear to favour the use of vulcanised bitumen cables, because of the electrolytic action of continuous currents on lead, and because of the spreading of a fault due to the hygroscopic nature of paper insulation. Both these objections presuppose that faults will happen. Vulcanised bitumen may decentralise, but this is least likely to occur when the cable is supported vertically, as in a pit shaft.

The Home Office rules permit the use of concentric cables with the outer conductor earthed, and for continuous-current or single-phase alternating systems we should regard this as the best possible from an electrical point of view, using concentric paper-insulated lead-covered and armoured cables.

In THE ELECTRICIAN " MINING ISSUE" for July 10, 1908, the practice of some cable manufacturers is quoted. Messrs. Siemens Bros. & Co.'s experience is that armoured paper lead-covered cables prove entirely satisfactory. They use their standard cables for all mining work, and supply large quantities to collieries in the North of England. Messrs. W. T. Henley's Telegraph Works Co. have supplied armoured cables insulated with impregnated paper protected by a vulcanised bitumen

sheath, the cables being single, three core or concentric ; this firm also supply all bitumen cables for mining work. Messrs Johnson & Phillips employ vulcanised bitumen cables, which have proved entirely successful. They also illustrated a three-core high-tension cable insulated with paper and bitumen, double-wire armoured and served with compounded yarn. Messrs. Callender's Cable & Construction Co. supply a vulcanised bitumen cable armoured with manila rope, which is non-shrinkable and water-resisting. This reduces the weight of the cable and also enables single cables to be used for alternating work. which is not practicable with steel armouring. The St. Helens Cable & Rubber Co. supply a double-wire armoured cable insulated and sheathed with " Dialite," a speciality of the company's. The British Insulated & Helsby Cables Co. supply a cable which is armoured with a hard cord braided on to the cable. Finally, in an article in the same issue by Mr. J. H. C. Brooking, a cable supplied by Messrs. W. T. Glover & Co. is described, which is all bitumen insulated, three core and armoured. A trailing cable by the same firm has rubber insulation next the conductors, and over and between this vulcanised bitumen, the whole being protected by leather braiding.

Along the roads the cables are generally suspended by leather or other flexible material ; the chief trouble is due to mechanical injury from subsidences and falls of stone from the roof, &c. All cables, and those of vulcanised bitumen in particular, should be supported at very frequent intervals, the exact distance depending on the weight of the cable. The Home Office rules say that the suspension shall be " in such a manner as to allow of the cables readily breaking away when struck, before they themselves can be seriously damaged." Flexibility of the cables is an essential feature.

Trailing cables are often of vulcanised rubber protected by leather or steel armouring. The chief point is to have a cable capable of much bending and rough usage without the insulation cracking or being cut. The St. Helens Cable Co. supply a trailing cable protected with a rubber cab-tyre sheath, which has been found very suitable for the generally extremely severe conditions met with at the coal face.

Lead sheathing and armouring are useful in a mine because

they provide a convenient earth for motor frames, &c. It is essential to make the armouring electrically continuous. Galvanised iron wire is usually employed, double on the shaft cables and single on the road cables. Trailing cables must contain an earth wire independent of the armouring of the cable.

Cab-tyre Sheathing.

This material, patented by the St. Helens Cable Co., is used as a protection for rubber and paper-insulated cables, and is intended for use in specially difficult places ; such as trailing cables for coal-cutters, the wiring of street cars and chemical works, public baths, street lighting and traction pillars, and anywhere under water.

Good rubber will last an indefinite time, if protected from moisture and air ; thus we have found the rubber in lead-
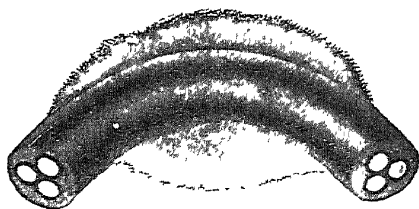
Fig. 105.—Cab-tyre Sheathed Three-core Cable.

covered rubber cables perfectly sound after years of use. For trailing cables and in other cases, lead and bitumen as a protection for rubber are unsuitable because they themselves cannot withstand rough usage. Cab-tyre sheathing will stand any amount of knocking about and trampling on, and it is quite impossible to kink it.

Whilst it appears to be made of vulcanised rubber, mixed with mineral substances, it has properties different from those of ordinary vulcanised rubber, as used for cable insulation.

We treated some samples with caustic potash and for the limited period under observation they did not swell up like ordinary rubber does. This we should regard as indicating valuable non-absorption properties. The sheathing appears to be unaffected by either organic or inorganic acids.

It has been treated with ozone for several hours, and the length of stretch before breaking has been found to be hardly affected. Ordinary vulcanized rubber almost always shows marked deterioration after this treatment, a few hours of which is said to be equivalent to many years exposure to the atmosphere.

The sheathing also differs from vulcanized rubber in that it has a lower insulation resistance. It can only be cut with a sharp tool, and is not likely to be injured in this way, unless intentionally.

It is slightly affected by lubricating oils, which cause the sheathing to swell, but this appears to be the only deleterious matter in common use that has any perceptible effect upon it. After an extended experience of cables sheathed with this material, used for travelling cranes and for supplying portable hand lamps on reinforced concrete structures, we had only one experience of a breakdown; this was when a length of cable got between the metals and the wheels of a 10-ton travelling crane. We have also seen the cable successfully used under sea-water, cleated to the walls of a dock, and buried in harbour mud.

CHAPTER VIII.

LAYING OF CABLES AND DUCTS.

General.

The most difficult problems in main laying are met with in the principal streets of large towns, and the electric supply engineer, coming, as he does, last of all in the demand for space, sometimes finds but little choice in the matter. Tramway lines may occupy a large part of the carriage-way, and there may be main and distributing gas and water pipes, with services taken off them at various levels; drains of all kinds promiscuously laid, telephone and telegraph pipes. and tramway feeders. In the midst of this medley accommodation must somehow be found for the electrical distributors, usually on both sides of the road, and in many cases provision has to be made for feeders, pilot wires and street lighting cables in addition.

Feeders are often laid in the roadway, as they need not, in the natural order of things, be again disturbed; but it is nearly always best and cheapest to lay distributors in the foot-path, for the following reasons :—

1. All service leads are shorter, and therefore cheaper.

2, Cables can be laid much shallower than in the roadway.

3. The ground will be much drier round the cables.

4. There is less excavation, and the work can be done more cheaply and quickly.

5. A proper drawn-in system for distributors is almost impossible if installed in the carriage-way, on account of the great cost of the necessarily heavy pits and covers for draw boxes and service connections.

6. The cables are more readily accessible for connections and repairs.

7. There is generally more room, as gas and water pipes are nearly always in the carriage-way.

8. The permanent reinstatement is usually cheaper than that of the roadway, and can be done once and for all.   A trench in a roadway takes time to settle, and if filled up in wet weather has to be gone over several times afterwards to get a good road surface.

After deciding upon their situation, one of the first questions that arise is the minimum safe distance which should separate the cables from gas or water pipes.   The mains engineer should be particularly careful to avoid gas pipes, on account of the danger of explosions if they are injured by electrolysis, and naturally the owners of all other pipes are as much concerned about the safety of their property.

If a pipe is within 2 in. or 3 in. of a cable it may be burnt through by a fault, but even at a distance of 4 ft. or 5 ft. it is not immune from danger.   The diagram (Fig. 121) in the section on fault localising shows how the potential of earth varies as the distance from a fault increases, so that at a radius of 7 ft. there is not sufficient potential gradient to cause any danger.   It is, however, as a rule, impossible to keep 7 ft. away from all pipes, and on a properly maintained network it is quite unnecessary, because a fault can be located so quickly that there is no time for much electrolytic damage to take place before it is disconnected.   Six inches of intervening earth is reasonable, but even this cannot always be maintained, in particular where cables are laid in footpaths above cellars, owing to the existing gas and water services.   One advantage of *insulating* ducts and troughs is that they may be laid with safety much closer to other pipes than those made of clay, for instance.

Apart from the risk of damage due to the proximity of the various pipes, the question of their respective accessibility should be carefully considered.   Electric cables must not be laid above any existing drains or underground works, and to guard against this the trial holes should be probed with a steel bar, to make certain that the sub-soil is clear.

When it is necessary to cross other pipes, this should be done at right angles ; if the cables cross near a joint in the pipe this should be at the socket end, so that it can be re-staved at any time.

Preliminary Preparations.

Before opening any ground to lay cables, notices and plans must be sent to the various authorities. These may include the gas and water people, the Postmaster-General and the road surveyor. It is as well to bring the foreman and a few men to the job the day before the gang commences, and let them open up trial holes on the proposed route in order to find a clear course. Often the position of existing pipes can be ascertained previously from the different authorities, but in old streets this is never the case, and a number of pipes, particularly drains, will be discovered of which there is no record.

When the main body of men arrives, the track should be marked off ready, and they can at once get to work. We do not consider it a good plan to let each navvy open up a section of trench by himself, because the pace will then be regulated by that of the slowest. It is better to mix the men's work up as much as possible, so that it is not easy for them to recognise when the too energetic members of the gang should be advised to slow down.

The length of trench that can be opened at one time depends on the nature of the traffic and on the police regulations, but usually 100 yds. or so is sufficient. The work must be safely barricaded, and for this purpose wooden trestles and planks are to be preferred to iron spikes and ropes, which are sometimes dangerous. All bridges, &c., over the track should be carefully fenced. Corporations are particularly liable to claims for damages, and generally have to pay, so that extra time and trouble on barricading, &c., is not wasted. Canvas screens should be used to protect the passers-by and shop windows from the fragments that fly when a hard macadam or concrete road-bed is broken up. It is also well to make a note of all broken windows in a street before beginning work, as fraudulent claims for damages have sometimes been made. The men must be impressed with the necessity for reporting any pipes they may accidentally damage, and they should not be penalised for this, otherwise they will cover up the damage with soil, and when, later on, it is inevitably discovered, the cost of rectifying it will be much greater than if it had been reported and admitted at once. The position of gas and

water services can generally be found from the stop cocks, and should be chalked on the wall for the men's guidance.

Laying of Ducts.

The trench being opened, some fine soil is riddled into the bottom to serve as a bed, and the pipes are then laid in and jointed.   If rows of single pipes are used, they should be kept everywhere apart with the joints staggered, and distance pieces of wood or broken clay pipe put in here and there. This prevents a bad short circuit between cables in adjacent pipes, and represents an advantage over composite ducts.* All ducts must be laid so as to drain into draw boxes, and any dips or hollows in them are quite inadmissible.   The slope must be such as to drain from one box to another, or high in the middle, so as to drain both ways into a box at either end.   Two feet of depth is enough for cables laid in carriage-ways, or less if they are concreted.   In footpaths it may be much less, and we consider that under flagstones the pipes containing the cables should be visible as soon as the stones are lifted.   There will then be less risk of *accidental* mechanical injury.   A spirit level is used in setting each length of duct so as to keep the " run " right.   To facilitate the drawing in of cable, ducts should always enter and leave a draw box at the same level.

If concrete is used as a protection, it may be made up of 1 part cement to 6 or 7 parts sand and gravel (by volume). If the concrete is intended to save the pipes from a crushing strain, like that caused by a steam roller, it should be placed underneath and packed well round the sides and between, as well as on the top, so as to form a kind of bridge.   If it is intended merely as a protection from picks, it need only be placed on the top and at the sides.   In any case, the concrete should have a smooth surface, and thus be easily recognised by any workman opening the ground later as something to be respected, and not to be smashed up as a casual obstruction.

A smoke-testing apparatus, similar to that used for drains, should be used on every length of pipes laid before filling in. This is a very sensitive test, and will show up any bad joints or fire cracks.   When this test has been made, the ground is filled in, first with sifted earth. which is carefully packed round

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* In America, cables are usually supported on carriers round the sides of manholes, but we have rarely found this to be necessary.

the sides and between the pipes ; more earth is then shovelled on and lightly rammed or punned—very carefully at first or the joints will be spoiled. When the trench is nearly full the ramming should be as vigorous as possible, and two men should be ramming for each man shovelling in soil. In dry weather more stuff can be got back if water is mixed with it, and the surface of a macadam road is generally washed in with water.

Laying Mains on the Solid System.

When laying cables " solid " there are one or two points to notice. The troughs are first laid in, jointed and bedded on sifted earth. The saddles can then be put in place, being stuck down with little patches of bitumen poured in hot. If this be done the cables must be drawn in *alongside* the troughing, and afterwards lifted into position.

Those who have not had actually to do this kind of work always suggest that the drum of cable should be rolled along over the trench and the cable paid off direct, forgetting that it has, at least in towns, to be threaded under pipes crossing the trench at right angles. The other method is to draw the cables into the troughs and afterwards to slip the saddles under. Perhaps the troughing is kept cleaner by the first method, as loose soil is very liable to be knocked into it at all stages of the operation. To prevent this, strips of canvas are often laid along the sides of the trench.

Before filling in the bitumen everything should be perfectly dry and clean. We think, if lead-covered cable is used, there should be no braiding on it, because this may act as a capillary passage for moisture to travel along the cable, and also because it is nearly impossible to dry it properly after a shower of rain ; and, since the trench cannot be kept open indefinitely, the work cannot be satisfactorily carried out in showery weather. Braiding would appear to be far more necessary for conduit work, where the cable may have to be drawn in and out several times, and cannot be examined after it is pulled in.

If the cable be pulled alongside the troughs first, it can all be examined for injury, and cleaned whilst it is being lifted into its final position. The saddles should be from 1 ft. to 2 ft. 6 in. apart, being nearer together the more flexible the cable.

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The first pouring of bitumen should be very hot and thin, so that it is sure to get underneath the cable ; if it is not hot enough it is very liable to chill and partly solidify on first coming in contact with earthenware or lead, and thus air spaces may be formed.   After this bitumen has hardened a little the troughs may be finally filled up with bitumen not so hot, the right temperature being that at which it is easily poured (from 250°F. to 300°F.).   The cables are liable to buckle with the heat if the troughs are filled right up at first, and they must be watched during the first filling, and, if necessary, pressed into their proper position with sticks.   If the troughing is covered with bricks or tiles, they are generally put on whilst the compound is hot, so as to make them stick in position.   If the troughs are laid on a gradient, it is necessary to start at the bottom and to work up hill when filling.   The Departmental Committee on Electric Mains Explosions, appointed by the Board of Trade, recommend, at the conclusion of their report (*see* THE ELECTRICIAN, July 10, 1914) that separate mains for continuous current supply should not be laid on the solid system below impervious pavements or close to the walls of houses ; that easy bends should be laid at corners, and the bitumen or pitch-compound should be poured after the straight lengths have cooled ; services should be taken into houses (preferably by the use of armoured cables) in such a manner that gas cannot enter.

The committee regard a pavement of concrete or asphalt as impervious, and a flagstone pavement as pervious.

In our experience flagstones are frequently impervious, and we have seen many examples of explosions that have occurred beneath them.   When there are cellars under the pavement, flagstones are frequently specially " pointed " with cement to make them impervious to water.

Where " solid " cables enter a brick pit they must be led through glands of some kind, since the bitumen will always tend to flow, even at ordinary temperatures.   Asphalt forms a suitable material for the glands ; but wood should be avoided if possible, as it always gets wet, and the cable may then be damaged by either electrolysis or chemical action.

The last two or three feet of the cable outside the pit should not be laid " solid," but in a pipe ; this prevents it from being sharply bent where it leaves the " solid " trough, and it is held

rigid. If the cable has to be often handled for disconnecting purposes, it is sure to give way just where it leaves the " solid " should this precaution be neglected.

Laying of Armoured Cables.

Armoured cables are the easiest to deal with. After they are laid in position, two or three inches of soil are sifted over them and the protecting boards then put on. It is sometimes said that armoured cables should not be laid in clay, as it attacks the armouring. Our own experience is the reverse of this, and we should suppose that the bed of sand, recommended as a remedy when the soil is clay, would form a natural drain in the ground, and result in the accumulation of moisture round the cable, thus affording an opportunity for many dissolved substances to be brought into contact with the cable, some of which might be harmful.

On a three-wire system, if single cables are used, it is usual to adhere to some definite order of laying the cables relative to each other. Thus the positive cable may be made always the most northern or eastern, the negative the southern or western ; or the positive may be always the inside cable, *i.e.*, next the houses. The latter method introduces an ambiguity when the cables cross a road, and necessitates more crossing of the cables themselves than the former.

Installation of Drawn-in Systems.

If the ducts have not had yarn threaded through as they were laid, they must be wired so that the hauling rope can be drawn in. This is done by pushing a No. 8 or 10 gauge iron wire, bent into a hook at the end, into the duct from either side, and when they meet in the middle the wires are twisted in opposite directions until they catch. An 80 yds. run of ducts can easily be wired in this way.* Lengths of canes screwed together, as used for drains, are also useful, especially for very long lengths, and when additional cables are being subsequently drawn in.

When the hauling rope is ready the drum is mounted on jacks, or on its carriage, a few feet from the draw box and

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* 120 or 140 yds. can be wired if the ducts are small. The larger the duct, the more difficult it is to wire.

behind it, which prevents the cable from being rubbed against the edges of the duct or pit (*see* Fig. 106).   Men are stationed to revolve the drum at the proper speed and watch that the cable does not foul anything when being fed into the duct.   With a heavy cable a wooden batten is used for this, as shown by the arrow in the figure, and of course the pulling is done very slowly.

A heavy cable must be liberally greased as it goes in, petroleum jelly being excellent for this purpose, as it has no injurious effect on the lead.

It is preferable to attach the *core* of the cable to the loop formed at the end of the rope.   This is done by dividing up the copper strands into two bundles, which are passed through the loop in opposite directions and then bound back on themselves with copper wire.   If the duct is wet, a mop should first
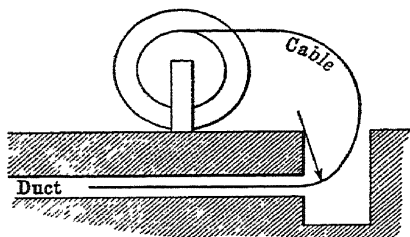
FIG. 106.—SHOWING RELATIVE POSITIONS OF CABLE DRUM AND DRAW BOX.

be pulled through to clear it.   The actual pulling may be done by hand or with a winch.   Hand pulling is generally the quickest, but for long lengths of heavy cables a winch is necessary.

When drawing in by hand the men should be well spread out on the rope, and should be taught to time their efforts, so that they pull together.

When adding to the number of cables already in a duct, it is better, as mentioned above, to pilot the hauling rope through by means of screwed rods, as a wire may twist about among the cables, so that the new cable is threaded amongst the others, which may not only damage them at the time, but may also prevent any individual cable being withdrawn at a future date.

Cables, particularly those with impregnated braiding, sometimes stick to the pipe or other cables, and cannot be imme-

diately pulled out. The sticking is not confined to one place, but is due to adhesion along the whole length. The following device will often overcome this difficulty.

An iron wire is pulled through the duct and a loop formed at one end, which is passed over the sticking cable. If the wire be now pulled from the other end the loop is pulled through, encircling the cable, and cuts away the adhering compound (Fig. 107). If there is a bend in the pipe near one end, the cable
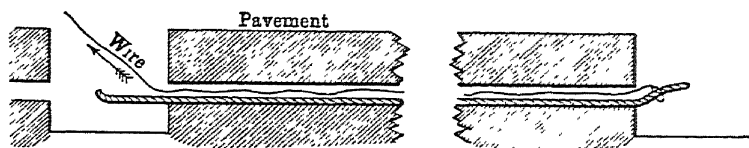
FIG. 107.—DIAGRAM SHOWING METHOD OF FREEING AN ADHERING CABLE

drum should be mounted at the opposite end, so that only a short length has to be pulled round the bend.

Installation of Cables in Mines.

The installation of mining cables depends on the character of the mine, depth of shaft, &c. The simplest way of dealing with the shaft cables is to hang them from a special suspender at the top, but this is only applicable to armoured cables in short shafts. The armour, carrying as it does the whole weight of the cable, is subjected to a continuous strain, which may in time stretch it so that the insulation is impaired. This method, although cheap, is not to be recommended as the most permanent, but if the cage guides are wire ropes and there are no stays to cleat the cables on to, there may be no choice in the matter. It cannot, however, be used in narrow or very deep shafts. One advantage is that falling bodies are unlikely to damage it, owing to its having a certain amount of give and take.

A suitable suspender is described by W. R. Morton.* " The suspender best suited for the job is in the form of a cone, bored in the centre to take the cable over the armour. Over the half rounded top of the cone the armour wires are bent back and taken down the outside. The outside smallest diameter of the cone should be sufficient to permit all the

* THE ELECTRICIAN, October 29, 1909.

armour wires to lie side by side without overlapping. This cone, with the armour wires correctly bent into place, sits in a taper seating of the same taper as the cone and provided with wings bored to take the D links of the supporting chains. The seating should be carried up above the top of the cone, and the cup thus formed filled with bitumen or other waterproof compound to prevent corrosion at this point."
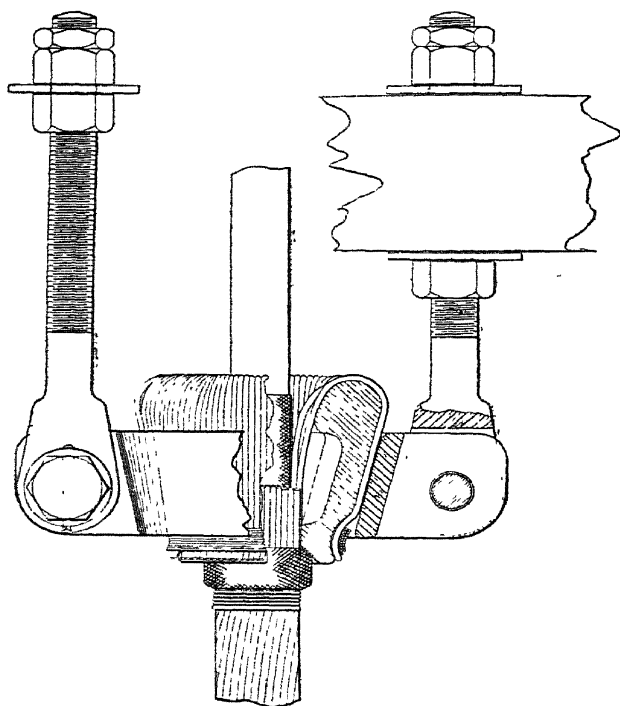
⅕ FULL SIZE

FIG. 108.—SUSPENDER FOR SHAFT CABLE.

Fig. 108 shows a cable suspender used by Messrs. Siemens Bros.

Another method of installing shaft cables is to cleat them on to cross-stays or buntons, the cleats used being of wood each from 2 ft. to 10 ft. long, their distance apart probably regulated by the stays and the more numerous they are the better. The cables are fixed behind the stays, and are thus,

to some extent, shielded from falling bodies. Care should be taken not to pinch the cables too much in the cleat, and the choice of wood is of some importance, pitch pine being suitable and oak to be avoided. The cleats are in two parts, bored out to about the external diameter of the cable, a common design being illustrated in Fig. 109.
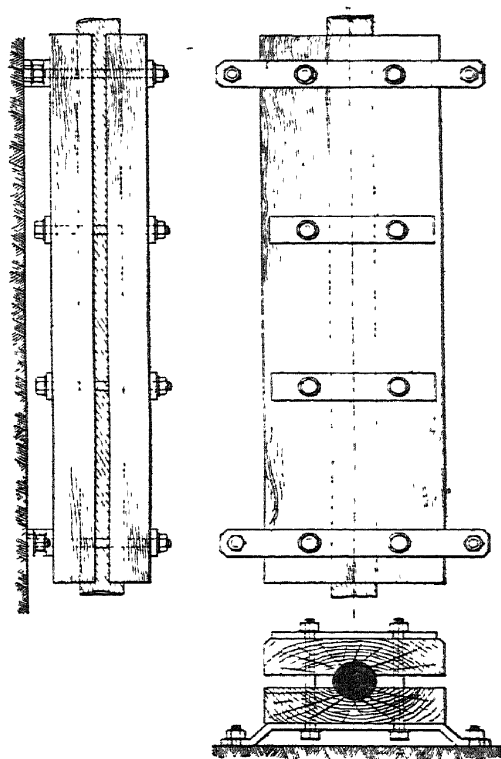
⅛ FULL SIZE.

FIG. 109.—CLEAT FOR SHAFT CABLE.

Another method is to use tarred wood casing, similar in principle to that for ordinary house wiring, except that the cables are a tighter fit in the grooves. The work should be periodically painted with tar.

Another method, not always possible, is to instal the cables " solid " in wood casing filled up with bitumen. A successful instance of this method is at Parton Collieries, Whitehaven,

an armoured, paper, lead-sheathed cable being dealt with in this way.* Each length of casing is filled solid with bitumen before the next length above is fixed. Owing to the difficulty experienced in filling the casing the bitumen should be made very hot and fluid. There is a difficulty in keeping the casing compound-tight, on account of the quasi-hydrostatic pressure exerted by it, especially when the height is considerable ; but this trouble can be overcome by the insertion of wooden glands at intervals. We have seen instances of the wooden capping having been burst off by the weight of bitumen, even with quite moderate vertical distances.

Shaft cables may also be installed in iron pipes, and although this affords an excellent mechanical protection at first, when the cables may be sufficiently " wavy " to grip the pipes at the sides, they will eventually straighten owing to their own weight, and the top suspension should thus be designed of ample strength for this ultimate condition.

With simple suspension from the top, the drum may be mounted on the cage and the cable payed out as the cage descends. Some braking arrangement should be used to prevent the cable loop revolving the drum by its own weight. The method is also adapted for the cleated system, but in many cases the cage is not available for the necessary length of time. A minimum of strain is put on the cable by this method, whereas if the drum be taken to the bottom of the shaft, and the cable then pulled up, it has to carry its whole weight before it is cleated. W. R. Morton† recommends, as the safest method for cleated cables, the use of a wire rope, controlled by a haulage engine. The cable is lashed to the rope at intervals, the engine being stopped for this purpose. The drum is mounted close to the pit, and the cable fed on to the descending wire rope, the movement being controlled by a brake.

Joints should be avoided, but in deep shafts, where they are a necessity, the cable lengths should be ordered so as to bring the joints at headings, or, if this is not possible, a special chamber should be cut in the wall, big enough to give plenty

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* G. G. L. Preece, " Electric Cables for Collieries," " Iron and Coal Trades Review," 1906.

† THE ELECTRICIAN, October 29, 1909

of room to a jointer and mate. If the joint must be made on the wall of the shaft, the cable both above and below the joint should be cleated with several good long cleats,to take all weight off the joint, which should be protected by a stout wooden fender. A variety of methods are employed to instal cables in the roads. G. G. L. Preece, in " Electric Cables for Collieries," says : " Where there is a good bottom to the roads and no danger of floor movement, a splendid permanent job can be made by burying the cables underground, out of harm's way from tubs running off the line. In non-fiery mines these troughs can be filled solid with bitumen. The usual plan with single cables is to run the two conductors along opposite sides." Cables are frequently suspended to the roof or to timber props along the sides. The suspenders should be designed to break away easily if roof falls occur, and should have a large bearing surface. The closer they are put together the better, and the cable should be allowed to lie fairly slack between them. The suspenders are made of leather or impregnated yarn or canvas, and may be held by hooks or nails driven into the timber. Earthenware insulators are also sometimes run, or a shell may be cut in the sides to carry the cables.

No special difficulty presents itself in making joints in underground cables. In fiery mines sweated joints cannot be made, and clamp fittings in joint boxes are generally used. When jointing compound has to be used in a mine, and cannot be heated locally, it must be conveyed from the bank to the joint box in some non-conducting jacket. Buckets placed in tubs filled with sawdust have been used with success.* " Safety " cables have been designed for mining work which are supposed to prevent any sparking taking place where a live cable is cut. " The general method is to provide a small auxiliary cable in parallel with the main conductor, which, in the event of a fall cutting the cables, is arranged to break either before or after the main conductor, and in each case actuates a magnetic cut out, which opens the main circuit."†

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* W. T. Anderson, " Trans." of Institution of Mining Engineers, Vol. XLV., p. 141.

† A. T. Snell, " Electric Motive Power." For detailed information on safety cables and mining work generally the reader is referred to this. book in " THE ELECTRICIAN " Series.

CHAPTER IX.
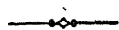
RECORDS OF MAINS AND ALLOCATION OF COSTS.

The importance of accurate records of underground mains and boxes cannot be over-estimated. On a large network, plans have to be referred to many times daily. The methods adopted by large undertakings have generally been built up from some very simple beginning, which has been elaborated as the necessity for accurate plans came to be recognised. Most systems in use bear a family resemblance to the one described below, with variations in detail.

A number of skeleton maps of the district served are first obtained. On one may be indicated by a coloured line all the distributors, with different coloured circles representing feeding points, disconnecting boxes, network fuses, &c., and a line in some distinctive colour may be drawn joining up the cutting point fuses, and thus indicating the limits of each feeder district. This map will be used for obtaining a comprehensive view of the whole network when planning extensions or alterations, and also when splitting up the network to locate faults.

A second map may have all the feeders drawn on it, a third may show all the public street lighting, and a fourth the high-tension cables, feeding sub-stations or buried transformers. Obviously the more " mixed " the supply system is the more maps would be used. The maps are all ruled into numbered squares corresponding to sections of the 10 ft. scale Ordnance maps. Thus any street or cable on which information is required is first booked up on the skeleton plan, which gives the number of the Ordnance map on which it appears. These skeleton plans are conveniently kept clean by hanging them against the wall one behind the other, and allowing them, when not in use, to roll up into a box, like roller blinds.

The Ordnance maps, mounted on strong linen with bound edges, are kept in a series of drawers, arranged so that any particular number is readily found. On these are drawn all the ducts, manholes, cables, &c., different kinds of ducts or methods of laying cables being distinguished by employing different coloured inks. All service lines and buried joints are clearly shown, with as much detail as possible. The scale on which the boxes and cables are represented is sufficiently accurate to measure up the position of a joint, say, within 1 ft.

Where there are a number of cables crossing each other, or several joints at disconnecting boxes, transformers or sub-stations, or in any case where the scale of the Ordnance map is too small for the drawing to be clear, a reference number is given corresponding to a given page in a sketch book, where all the details are drawn to a larger scale and dimensioned. These books are kept in their proper order in a bookcase, so as to be readily available.

The cross-sections of all cables are marked on the Ordnance maps and the numbers of houses inserted where known, so that a new consumer can be located on the map and measurements taken of the length of service line and any extension of main required.

For new work, or alterations, the mains engineer writes up, preferably in a carbon copy-book, the particulars, such as section and number of cables, polarity of service, method of installation, number and size of boxes, &c., and gives it to the foreman in charge, together with a tracing from the Ordnance map showing the route to be taken, and also includes in the instructions a job number for cost-keeping. On the completion of the work this is returned by the foreman to the engineer, who notes on it any alteration from the original design, signs it and passes it on to the draughtsman, who enters the particulars on his maps, together with the measurements and sections he has taken during the progress of the work. The sheet is then handed on to the costing clerk, who checks from it the actual orders received for material bearing the particular job number, and if the material given out tallies with the work shown on the sheet the latter may then be destroyed. The clerk should also work out the cost of labour per yard of trench

opened, and should enter up the date at which the work was done and the names of the foreman, jointers, &c., employed on it.   The costs books are stored and the outsides dated, and if the date of the completion of all work be entered on the Ordnance maps, the particulars of any work can readily be referred to in the costs book bearing that date.

If the meter department keeps the " balancing " cards for a three-wire or multiphase system, the instructions sheets must pass through that department before going to the costing clerk, so that a record may be kept of the polarity of the new services.

To ensure the return of all the sheets issued, the mains engineer enters the number and title of each job in a book when issuing the sheets, and checks their return by this book.   The highest accuracy should be aimed at, and hardly any detail is too unimportant to note.   A knowledge of the number, size and position of pipes and other works in a street is frequently required, and it is thus useful to keep in a special book drawings showing sections of streets, or parts of them, which the under- taking has had occasion to open up when laying cables.

One of the most difficult of a mains engineer's duties on a large supply system is to allocate all the time and material to their proper accounts.   Thus, some of the work has to be allocated to capital account, and this must again be subdivided into mains extensions proper and services ; then, in the main- tenance account, renewals of cable must be distinguished from ordinary up-keep, chiefly on account of the income tax charges. There are also public lighting capital and maintenance accounts, and other work the cost of which is recoverable from consumers or other authorities, and probably sub-divisions of some of these.

Thus, even on everyday extension work involving services, the time and material has to be analysed and allocated to two different accounts.

The foreman in charge of a job should be the only person to issue orders for materials for that job, and should mark them all with the job number.   The return of all unused or scrap material to the stores should be done through him, and his returning notes also numbered the storekeeper having in- structions to refuse all material returned unaccompanied by an

order. These orders come back to the mains engineer from the stores, and are signed and allocated by him. Similarly, the foreman numbers the time sheets of the men, which are then allocated by the mains engineer; charges for cartage are similarly dealt with. It will be abundantly clear (on an extensive network at least) that great care must be given to the booking up of costs if accurate and instructive figures for future guidance are to be obtained. The method of arriving at the proper tariffs to impose on a public supply system depends essentially on the correct allocation of all expenditure.

CHAPTER X.

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EARTHING, LOCATING EARTHS, AND EARTH INDICATORS.

Three-wire Networks.

It is essential that faults on any system of mains should be quickly located. Every extra 10 minutes' duration of even a small continuous-current fault may be the cause of others developing, perhaps a year later. Hardly any of the earlier networks were designed to facilitate the location of faults, and consequently, where they are extensive, this is often a lengthy business, and must, as a rule, be carried out at night. Most cable systems are now readily split up by fuse switches interconnecting the different feeder districts. These fuses, being designed to melt with heavy currents, are generally in pillars above ground, and thus convenient of access, so that one man on a bicycle can make a long list of disconnections in a very short time.

The most useful faculty to employ in fault finding is facility of deduction, coupled with an intimate acquaintance with the network.

Under the B.O.T. rules the third wire must be earthed, and the arrangement generally adopted is that shown in Fig. 110 or Fig. 111. In Fig. 110 a resistance of $\frac{1}{2}$ ohm to 3 ohms is inserted between the third wire and earth in series with a recording ammeter. The switch S_2 is normally closed, and when S_1 is also closed the absolute leakage current is indicated on the ammeter. In Fig. 111 the third wire is connected dead to earth through a recording ammeter until a prearranged value of the leakage current melts the fuse, when the indicating lamps, which may be arranged along the top of the switchboard, will light up. The Board of Trade regulation says that " the insulation shall be so maintained that the leakage current

shall not under any conditions exceed one-thousandth part of the maximum supply current, and suitable means shall be provided for the indication and localisation of leakage."

There are many modifications of the simple arrangements shown, which include adjustable resistances, two or more ammeters, a voltmeter and other switches and fuses. Unless it is desired to test the insulation resistance of the system, the arrangement in Fig. 110 is all that is necessary. If the two resistances are each half an ohm cold, the fault current can be limited to less than 250 amperes on a 500-volt system.
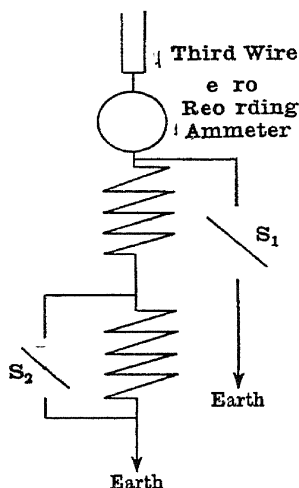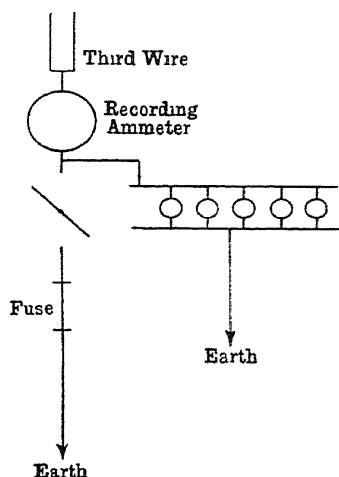
FIG 110.   FIG. 111.

There are several formulæ which give the combined insulation resistance of a network.

The " Russell " formula is $F = \dfrac{V_1 - V_2}{C}$.

V_1=potential of third wire to earth measured on a high-resistance voltmeter when the earth connection is broken.

V_2=potential of third wire to earth when a current, C, is flowing through the earth connection.

F=insulation resistance in ohms. This value of F can be read direct on the ingenious Groves ohmmeter.

For other formulæ Raphael's " Localisation of Faults on Electric Light Mains " should be consulted.

Tests of this kind are interesting, but their practical utility ·appears open to question. On an almost purely lighting network, a test made on a fine morning may give probably the true insulation resistance, but if it be repeated at night, when the load is on, an entirely different result will be obtained, as there will be a good deal of internal wiring included. Supposing the morning test shows a fall in insulation over the previous day. If the reduction is not sufficient to cause a definite earth current to flow through the earth ammeter, it is useless taking steps to locate it; if, ·on the other hand, it does cause a definite current, then the earth ammeter indicates a fault just as well as the test. On large networks, supplying a substantial power load, the value of F obtained at any time of the day or night varies constantly, but is always very near 0. Any attempt to attach quantitative importance to the figure obtained is absurd if the earth ammeter reading is normal.

It is, if anything, desirable that a large network should show a slight negative earth current when in a healthy state, the amount depending on its size and arrangement. In the con·clusions as to the condition of the network, based on the ammeter readings, this false zero must be allowed for. That state of affairs in which a positive and a negative fault just balance, so as to produce a normal reading on the ammeter for any length of time, is so improbable as to be not worth considering. As illustrating the false zero condition, a network which showed a negative leak of 3 amperes was thrown dead in sections, one section only (representing about one-twentieth of the network) being off at one time. No one section made any perceptible difference in the ammeter reading of 3 amperes.

A fault on the third wire, if very bad, will reduce the reading on the station earth ammeter produced by an " outer " fault, but will not prevent it showing some earth current, which is all that is necessary.

A recording ammeter, then, is sufficient to indicate the state ·of the positive and negative mains. It does not, however, show the state of the third wire main, but this may be tested

for periodically. Fig. 112 shows a convenient method. A few cells, or preferably a booster machine, are connected between the third wire and earth, giving a potential of anything up to 50 volts ; the current through the ammeter is an indication of the condition of the third wire. The instrument should read to within 0·1 of an ampere. It will be found that if the booster be allowed to run some little time with the positive pole connected to earth the current tends to rise, whilst if the connections are reversed the current tends to fall. This is an indication of the electric osmotic effect.
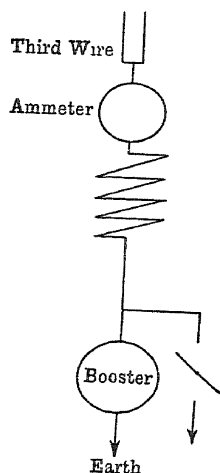
Fig. 112.

Another rough test consists in making an artificial earth through some lamps on the *negative* main, preferably at some distant feeding point. The earth current, as measured on an ammeter at the " earth " ought to correspond exactly to the extra earth current recorded at the station if the third wire is sound.

Someth ng may often be guessed as to the nature of a fault by a study of the earth ammeter record. In Fig. 113 the record A was due to a lift motor with the neutral ruse blown and an earth on the neutral side of the motor at the brush gear. B was a manhole full of water short-circuiting the three poles.
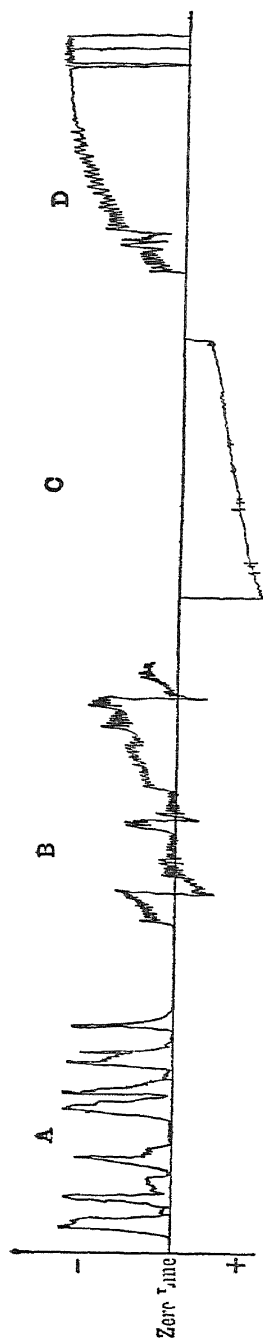
Fig. 113.

C was a positive fault on an armoured cable showing the usual tendency of a positive fault to get less as time goes on. D was a negative fault on a V.B. cable in a pipe. The disconnections indicated near the end are those made when it was being located.

Location of Faulty Section of Network.

The first step in finding a fault is to ascertain in which section of the network it is situated. There are several methods of doing this, and perhaps No. 4 of the following is the best.

1. The third-wire earth connection is broken, and the opposite pole to the faulty one is momentarily flashed to earth. The feeder ammeters on the faulty side are carefully watched ; the one that kicks most when the flashing takes place indicates the feeding point nearest to the fault. Part of this district is then disconnected from its own feeder and the flashing is repeated, and, if a neighbouring feeder now gives the largest kick, the fault is obviously in the section of network transferred. With a sufficient number of disconnecting boxes a fault may be narrowed down to a straight length of cable

A third-wire fault may also be located by this method, if there are neutral feeders each provided with an ammeter. Instead of flashing an outer main, the third wire may be connected and disconnected rapidly to and from earth, and the fault current may be detected on a feeder ammeter, if the feeder current is small and steady and the fault current fairly large.

This method can be carried out at times of light load only ; this with any considerable day load and a small earth means only between midnight and 6 a.m.

On some networks the third wire is broken, and each outer main earthed in turn through an ammeter, every day or every week, the readings obtained being an indication of the condition of the other two mains. Faults suspected to be on consumer's premises are sometimes cleared off by earthing the opposite main and so melting the consumer's fuses.

Intentional earthing of an outer main, with the third-wire earth broken would appear to be generally inadvisable ; it often breaks down other faults, chiefly in house wiring, and may cause fires ; it also appears to defeat the intention of the

B.O.T. Regulation with regard to earthing the third wire, as it brings nearly the full outer pressure into consumer's premises.

There is an instance of a supply company paying damages for a fire brought about by the attempt to burn out a consumer's fault in the way described above.

2. This method, due to Hopkinson, consists in testing the network section by section, feeding each in turn at one point only through three ammeters. If there is no fault, the *algebraical* sum of the three readings should be zero. If there is a varying load on, it is extremely difficult to read the three instruments accurately and simultaneously, and so a small fault is easily missed. A differential ammeter with three windings has been used with success, and gets over this difficulty ; it reads zero with no fault. This method can only be employed at times of light load, and is slow. It can be used for third-wire earths if a constant current is maintained through the fault by means of the booster shown in Fig. 112.

3. This method requires the use of switch fuses interconnecting each feeder district at the points of lowest potential. All these fuses are pulled out on the faulty side of the system only, so that each district is fed thrugh its own feeder only, on the faulty pole. One of three courses may now be followed.

(*a*) Each feeder switch may be broken for a moment in turn on the faulty side. The fault will go off when the switch which supplies the faulty district is broken.

(*b*) Each feeder may be put on to a separate bar in turn, and the voltage of this bar lowered slowly. A drop in the fault current as the voltage is decreased indicates the district containing the fault.

(*c*) A resistance (adjustable) may be placed across each feeder switch in turn and the switch broken. The fault current will fall in the case of the faulty feeder district ; (*a*) has obvious disadvantages, (*b*) and (*c*) are very much better, but can only be used when the feeders are lightly loaded.

4. This method is very quick and accurate. It can be employed at any time, and does not involve any interference with the supply. The arrangements for the test should all be permanent, so that on a fault occurring it may be located with as little delay as possible. Here, again, the feeder districts should be linked together by switch fuses in section pillars, and the

method further necessitates the use of two 'bus bars at the
station. Half the feeders are plugged on to one bar and half
on the other, with sufficient machines on each for its respective
feeders. There must be two third-wire bars, each with an
earth ammeter. The network is now split by means of the
fuses outside into two halves, entirely separate from each other
in every way ; the half containing the earth (which shows on
its own earth ammeter) is then transferred setcion by section
to the other bar, together with the necessary machines, until
the leakage current disappears from the one ammeter and is
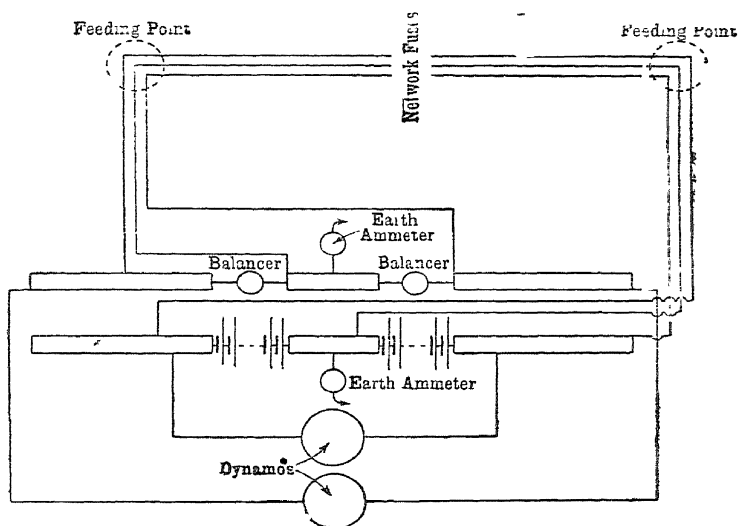
Fig. 114.

indicated on the other. The feeder district which affects this
change is the faulty one This district can itself probably be
subdivided, and so the fault can be reduced to a small portion
of network. The switchboard alterations are readily made,
whilst a man on a bicycle is making the disconnections outside.
Fig. 114 shows the arrangement of the board for two feeders
only.

A third-wire fault is easily found by this method by having
a booster machine running in *one* earth connection.

Having got the fault narrowed down to a small section, the further procedure depends on the method in which the cables are laid. If it is a drawn-in system, the fault will be readily discovered by inspecting the street boxes ; if there is no smoke, one is nearly certain to be able to smell the heated insulation, or to get a slight shock, or to notice other abnormal conditions. If the pavements are wet after a shower, a fault can frequently be detected by noticing a dry patch on the surface of the footpath. With lead-covered cables, however, what is frequently indicated is not the actual fault, but the place where the fault current is entering or leaving the lead. It is, of course, desirable to open the ground and examine the cables at such places as well as at the actual fault. Telephone and compass methods of locating a fault frequently indicate a similar place. The faulty place on a cable laid shallow under a pavement can often be found by feeling the surface of the pavement with the hand ; a fault current of 5 amperes flowing for two hours or so will make the pavement perceptibly warm to the touch.

When a fault occurs on armoured or solid laid cables in the roadway, all the openings made on the route of the cable by other people for the last few years should be looked up, as the fault is very likely to be at one of these places. In a particular instance there was almost indisputable evidence to show that a fault on an armoured cable was due to damage received during the laying of a pipe underneath it eight years previously.

If a network consist of lead-covered cables laid solid or drawn into insulating ducts, any fault can be at once located to a feeder district if the lead of all the cables in each district be bonded together, roughly insulated from earth and from the lead sheathings of all adjoining districts. Thus, on a fault occurring, the lead sheathing of the cables in any definite area becomes above or below earth potential. If a pilot wire, or preferably the insulated lead sheathing of one of the feeder cables, be connected to the bonded sheathing at the feeding point, and through a voltmeter to earth at the station end, the faulty district is readily detected.

When, by any of the above methods, the fault has been reduced to a single length of cable which is inaccessible anywhere except by digging, closer testing becomes necessary, and with some of the methods hereafter discussed great accuracy of location may be obtained.

Exact Location of a Fault in a Length of Cable.

́It is not proposed to discuss fully here the many methods of locating the exact position of a fault when it has been traced to a definite section of cable, as these are all given in Raphael's book on " Localisation of Faults in Electric Light Mains " (in " The Electrician " series). The principal tests are, however, given in summarised form for the sake of completeness and facility of reference.

1. *The Wheatstone Bridge Test.*—The usual connections are shown in Fig. 115. AB is a cable with a fault at E, and CD a sound cable which can be connected to AB at B to form a loop, ABDC. The adjustable arms of the bridge (AO and OC), in its most convenient form, consist of a high-resistance wire of uniform cross-section, fixed on a board, which carries a scale
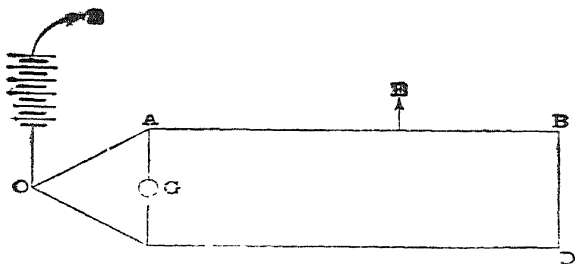
FIG. 115.

graduated in small divisions. A sliding contact, O, is provided, to which is attached one pole of the battery, the other pole being earthed. The ratio of the resistances OA and OC is the same as that of the corresponding lengths, and this simplifies the subsequent working out of the result. The slider O is shifted until there is no deflection on the galvanometer G (connected between A and C, and preferably with a key in circuit). When a balance is obtained the following relation holds good :—

$$\frac{\text{Length OA}}{\text{Length OC}} = \frac{\text{AE}}{\text{EB+BD+DC}},$$

or, if L=total length of loop in yards (AE+EB+BD+DC),

distance of fault from A in yards $= \text{AE} = \left(\dfrac{\text{OA}}{\text{OA+OC}}\right)\text{L}.$

The points to be noticed about this test are that the battery should be in the earth circuit, as shown, and not the galvanometer, thus eliminating any E.M.F. in the fault or in the earth between O and E.

The contacts at B, D, C and A must all be of negligible resistance ; a poor contact at any of these points might be equivalent to many yards of a big cable, and would spoil the test ; soldered joints are best.   The more sensitive the galvanometer, and the more finely divided the scale on the bridge, the more accurate will be the test ; the galvanometer should also have a low resistance, but all this will be useless if the length of cable is not accurately known and the contact resistances are small.   The battery should be of such an E.M.F. as to give convenient deflections.   If the test can be made from the station, a balancer or boosting machine can be employed ;
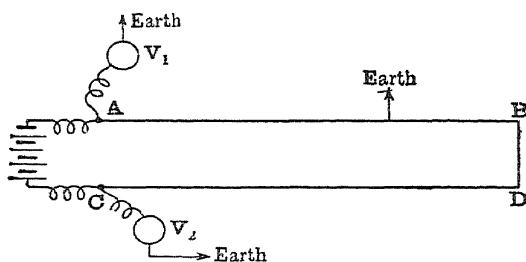
Fig. 116.

the provision of a suitable E.M.F. from portable cells is always a difficulty when the test has to be carried out in the street. There should be a key in the battery circuit to prevent the slide wire becoming heated and to prevent sparking at the slider, which would spoil the wire.   If the cable under test is a distributor supplying services, the consumers' fuses should be drawn, so as to avoid any connection between the conductors forming the loop except at B and D.   This test takes rather a long time to prepare properly, but gives very accurate results.

2. *Fall of Potential Method.*—There are many variations of this method which may often be useful, as it is not essential to have a loop.   Fig. 116 shows the connections for one method when a loop can be formed.   AB is the faulty cable and DC

a sound cable joined to AB at BD to form a loop ; a battery or dynamo is employed to send a conveniently big current round the loop. A voltmeter is connected between A and earth, and C and earth alternately, and constant deflections V_1 and V_2 obtained. The distance of the fault from A is then

$$\frac{V_1}{V_1+V_2}\times L \text{ yards,}$$

if L be the length of the loop in yards.

This is a good method, because one may make quite sure that everything is right. The deflection V_3 obtained by connecting the voltmeter across A and C should equal V_1+V_2, and V_3 should equal the calculated fall of potential round the loop, thus giving a check on the accuracy of the measurement of the cable length. Of course, to do this the current must be measured and the deflections reduced to volts. A Weston voltmeter reading up to 260 volts can be calibrated to read to 26 or 2·6 volts by putting suitable resistances in series with the " coil alone " terminal, and is very convenient for this purpose. There is nearly certain to be some E.M F. at the fault or in the earth which will affect this test ; but this can be allowed for. It can be measured by connecting the voltmeter from A or C to earth before the current is switched on, and it must then be added to one deflection and subtracted from the other. If the Weston instrument is used the direction of the E.M.F. can be obtained, and it will then readily be seen to which deflection it should be added and from which deducted. We have found such an E.M.F. to exist up to 0·6 volt, and we think it is generally in the earth rather than at the fault, as it can often be eliminated on a lead-covered cable by connecting the " earth " terminal of the voltmeter to the lead of the cable instead of to a water-pipe. A moment's inspection will show that the fact of (V_1+V_2) being equal to V_3 does not mean that there is no E.M.F. in the fault, since, if D_1 equals the first deflection and D_2 equals the second, and if there is a fault E.M.F.$=V_4$,

$$D_1=V_1+V_4 \text{ (say),}$$
$$D_2=V_2-V_4.$$
$$D_1+D_2=V_1+V_2=V_3.$$

If the fault is near the far end of the loop, and the fault E.M.F. be not allowed for, the test may indicate that the fault is in the sound half of the loop. The existence of an E.M.F. at the fault can be further tested for by reversing the battery connections, when, if there is no such E.M.F., V_1 and V_2 should be the same as before. The resistances of the joints B and D must be negligibly small and the resistance of the voltmeter should be high compared with the resistance of the fault.

Another variation of the Fall of potential method is shown in Fig. 117. AB is again the faulty cable, having a fault at E. A current of any suitable strength is passed into the faulty main AB, and leaves at the fault E. R is an adjustable resistance, A' is an ammeter and V a galvanometer. CD is any sound lead, such as a coil of 3/20 cable run along the surface of the road,
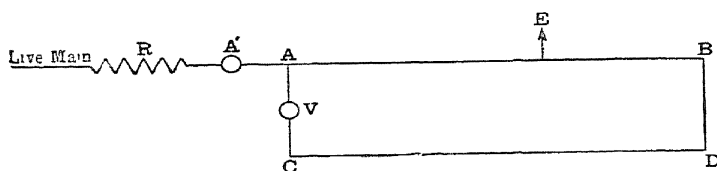
FIG. 117

so that CDBE is simply a connector to measure V, the difference of potential between A and E. The whole of the apparatus is now transferred to B, and a similar test made with exactly the same current, R being adjusted to this end, and A and C being connected together. V now measures the fall of potential in BE. The position of the fault is then readily calculated as before. This test is independent of any contact resistances, and also of any E.M.F. at the fault, but it can only be used to locate a fault through which a considerable current can be passed.

If there be two faults on a section, which is exceedingly probable after a heavy earth current on an armoured cable, any of the methods described above will indicate a mean position for the two faults intermediate between them and depending on their relative resistances. If the faulty cable has

several different cross-sections, the equivalent length must be found in terms of the largest section. For instance, if AB represents a 0·5 sq. in. cable (Fig. 118) and BC a 0·25 sq. in. cable, then the " equivalent " cable is represented by ABC'. BC' is twice BC when regarded as a 0 5. cable. If the fault then is located to E on the " equiva'ent " cable, BE must be recalculated in terms of a 0 25 cab e—*i.e.*, distance of fault from A

$$=AB+\left(BE\times\frac{0\cdot25}{0\cdot5}\right)=AB+\tfrac{1}{2}BE.$$

3. *Discontinuity without an " Earth."*—Such a case some-times occurs with potential or pilot leads and telephone cables. It may be approximately located by measuring the capacities of the two parts of the cable from each end. The cable is
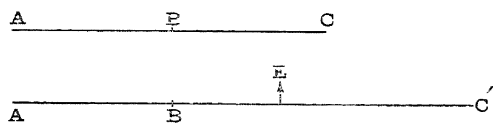
FIG. 118.

charged by a few cells and then discharged through a galvano-meter ; the swing of the galvanometer needle is proportional to the capacity of the cable. If d_1 be the deflection obtained at one end and d_2 that obtained at the other the distance of

the break from the d_1 end is $\dfrac{d_1}{d_1+d_2}$. l, where l is the length of the cable.

A short-circuit on a concentric cable will sometimes cause a discontinuity without an earth, the two conductors being clear of one another and of earth, and we have seen such a break fairly accurately located by this test.

When locating a fault on a distributor it should not be over-looked that the fault may be in a service cable, and, should the fault not be found in a service box indicated by the test, the ground should not be filled in until the service cable has been tested for insulation and its soundness verified. If the fault be

inaccurately located, so that on opening the ground there is no sign of it, the direction in which it lies may be seen, without cutting the cable, by passing a current through the fault from one end and holding a compass over the cable. If the fault lies between the leading-in end and the compass there should be no deflection. This test may be upset by currents travelling along the lead (or less likely the armouring), in which case a strip can be cut out of the lead. When the fault has been located to a definite length, it is a good plan, on a continuous-current system, not completely to disconnect the cable, but to maintain it 50 or 60 volts above earth potential until the fault has been located and removed. This helps to prevent moisture creeping up the cable, and is especially useful with jute insulation, which rapidly absorbs water if the cable is old. The faulty cable, if part of a three-wire system, can be connected through a resistance to a " live " positive main.
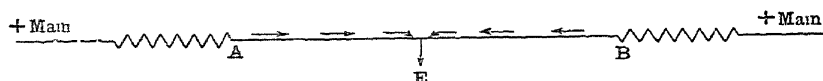
FIG. 120.

4. *Induction and other methods of Locating Faults.*—Other methods of locating faults may be briefly mentioned. If a cable is not laid too deep, and if the fault has a low resistance, the following method may be employed. A B, Fig. 120, represents the faulty section. The cable is made " alive " from each end and a current sufficient to deflect a compass needle is passed through the fault. If now the compass be placed on the road surface above the cable at intervals along its length, the deflection will be found to reverse at E, the fault. This method may be vitiated by currents travelling along the lead and armouring, but in spite of this objection we have seen some very accurate locations made by it.

Another method of locating faults depends on the fact that the fall of potential in the soil round a fault is very rapid. Thus, if the condition of a fault be artificially produced by running an iron bar into the ground and making it " alive "

with one pole of a three-wire system, it will be found that the potential between this live bar and a second bar 6 ft. or 7 ft. away will be nearly the full voltage across one side of the system. (*See* Fig. 121.)

In fault locating on this principle a high resistance voltmeter is connected to a good earth, say, a water-pipe or a tramway rail, and to a long flexible lead, which has a long knife blade

DIAGRAM SHOWING MEASUREMENT OF GROUND POTENTIAL NEAR ARTIFICIAL FAULT.
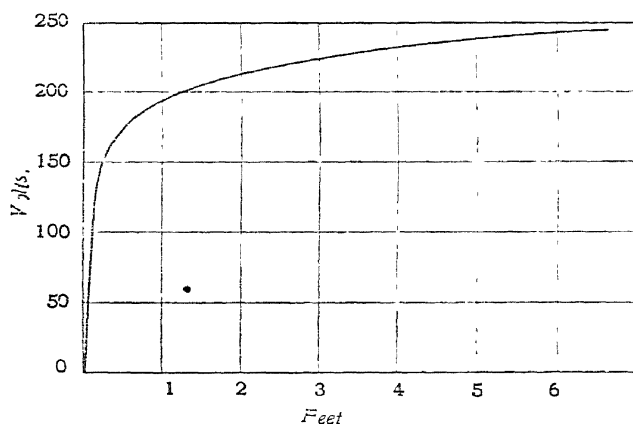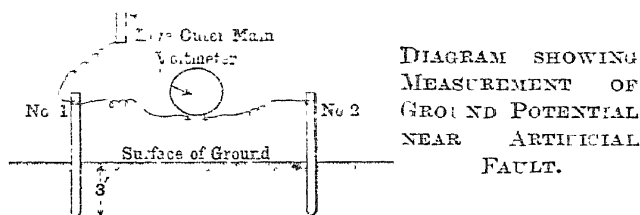
FIG. 121.—CURVE SHOWING VARIATION OF GROUND POTENTIAL WITH DISTANCE NEAR A FAULT.

attached to the other end. This blade is stuck into the ground at various points along the route of the cable and the voltmeter readings noted. The point where the highest reading is obtained shou d be the position of the fault. The faulty cable must, of course, be alive whilst the test is being made. This method may sometimes be usefully employed with non-lead-covered cables,

but may give inaccurate and uncertain result with a lead-covered cable, if the lead has become alive the readings obtain d may be the same all the way along the cable. In a particular case, on an armoured cable which had developed a fault this test merely indicated the place where the cable was nearest the surface.

The method has been described by W. A. Toppin,[*] and used by him with success. It has the advantage that a fault may be located without disconnecting the supply, and, indeed, it may sometimes be located and dug out before the connections for a loop test can be made.

5. *Telephone Methods.*—The " telephone method " may sometimes be usefully employed on a network which cannot be readily disconnected so as to isolate individual lengths of cable. It is carried out by passing an alternating or interrupted current into the network, which leaves by the fault. A coil of wire, with its two ends connected to a telephone is then carried over the route of the cables ; after the fault is passed the noise in the telephone, caused by the currents induced in the coil, ceases and the point where this takes place indicates the fault. This method again may be spoiled by the current after it has left the cable, travelling along some extraneous pipe, or along the sheathing of the cable. If the whole of the current is returned by the lead sheathing of a cable the effect would be completely neutralised. The coil of wire is often wound on a triangular framework, and one side of the triangle is held parallel with the cable ; a coil of, say, 3 20 rubber cable, as received from the makers, will sometimes do.

Many engineers obtain successful results with this method, but our own experience has been unfortunate. We have, however, seen it successfully employed in one particular case. This was on a length of lead-covered cable which tested earth, but on which, when withdrawn from its duct, there was no visible fault. One pole of the low-tension side of a transformer was connected to both ends of the conductor, and the other pole was connected to the lead at one end of the cable only. (*See* Fig. 122.) From A to B there was a slight noise in the telephone, due to the difference between the currents in conductor and lead ; from B to C there was a louder noise, and

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the point B where the change occurred was clearly defined and proved to be the faulty place. The lead (E D) was kept well away from B C. This test could perhaps be carried out on a lead-sheathed underground cable if a loop could be formed by means of a sound cable which did not lie alongside the faulty one, the sound cable being represented by D E in Fig. 122. The result might be inconclusive if the lead were well earthed on both sides of the fault. Probably its most certain application would be to the case of a concentric or multi-core cable which was short-circuited but not earthed, and in gene al fo " solid " laid cables it would have the best chance of success.

When a loop can be formed, the Wheatstone bridge method is the most accurate general test, and we should always use it and
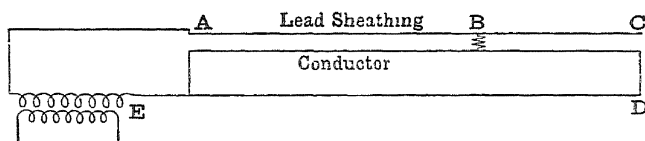
FIG. 122.

check the result by the first fall of potential method shown, the extra time taken over this being very little once the loop is prepared for the bridge test   If, on opening up the ground at the point indicated by the test, no signs of the fault can be seen for a few yards either way, the cable should be cut, and tested both ways, and it will often be found that there are two faults, one on each side of the break. If the outer conductor of a concentric cable is normally at the same potential as earth, there may be an earth on this conductor which is quite invisible externally ; and similarly there is sometimes a contact between the outer and inner conductors of a concentric cable, of which there is no external sign. Very high resistance faults, sometimes referred to as " testing low " rather than as an actual " fault," are nearly impossible to locate and may be " broken down " by applying a high alternating voltage to the cable.   Such a high voltage may be built up by connecting the low-tension coils of two

or more transformers in parallel and their high-tension coils in series.

Callender-Frampton System of Fault Localisation.

A system recently introduced under the above title is designed to secure the quick localisation of a fault on a distributing network by unskilled labour.

The system involves looping the main at each service joint into the building, where in a specially designed fuse box the *main* passes through a link.

The figure (123) shows the connections for one service, off a three-wire network.

Obviously, testing from one end of the distributor, sections of cable between services may be added or subtracted, by
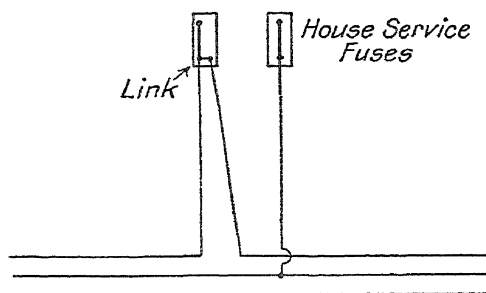
FIG. 123.—CALLENDER-FRAMPTON SYSTEM.

means of the links and the fault readily localised between two services.   If the main is fed from both ends, no consumer need be disconnected during the operation.   Particularly with long services, the system has the disadvantage of increased cost of cable per service and increased resistance of the distributor, and hence can only be used on small lightly-loaded networks.

A system which we have seen used successfully with solid-laid lead-covered distributors and service cables, and of which the last system reminds us, consisted of breaking the continuity of the lead at every service joint, and connecting (in accordance with a definite plan) the lead of the service cable to the lead of the distributor, on one or other side of the joint. The lead of the service cable and the lead of the distributor

being everywhere insulated on the solid system, on a fault occurring the lead between two services becomes " alive." " Live " lead is tested for at the service fuse boxes, where the lead of the service cable is exposed, with a high resistance voltmeter. We have not personally tried it, but we have heard it said by jointers that the human tongue makes a very sensitive indicator for this test.
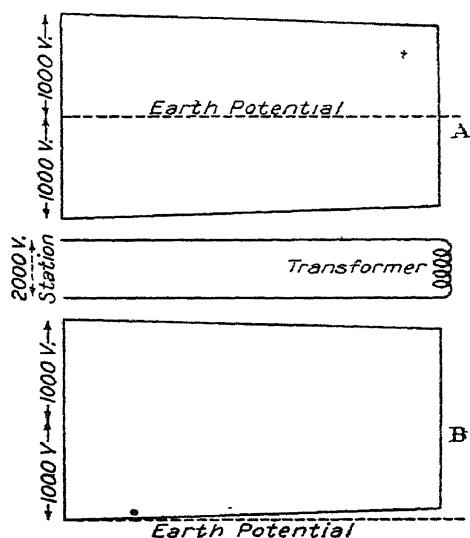
A. Main not earthed. B. Main earthed at station.

Fig. 124.

Earths on High-Tension Mains—Single-Phase Systems.

The high-tension mains on a single-phase system are required by the Board of Trade to be concentric, with the outer conductor earthed at the generating station. This fact prevents the use of any leakage indicating device, because the point of zero potential relative to earth is at the station end, and not the centre point of the consuming device. Fig. 124 illustrates this. The object of the regulation as to earthing the outer is to prevent injury by shock to any person acci-

dentally cutting into the cable. It also obviates the possibility of resonance effects which might occur under certain conditions already described.

A fault on the inner core of the cables necessarily implies a short-circuit. A fault on the outer conductor is then the only warning of danger, and must be removed as rapidly as possible before it develops into a short-circuit.

High-tension mains are thrown dead and carefully tested for insulation resistance once a week. This may often be done without interruption to the supply, at times of light load, where the mains feed into a ring. It is also possible if the secondary networks are interconnected or if duplicate feeders are laid.

A fault is easily located by one of the " loop " tests, or inductive methods described under three-wire systems, if its resistance is low enough. High resistance faults must be found by breaking up the main into sections by means of convenient switches and testing each section separately. When the fault is located to a section, an examination of joints or other fittings will generally reveal its exact location.

It is possible to get an approximate idea of the position of a bad earth on the outer main by measuring the potential between the outer and earth at various points distant from the station when the cable is loaded. One should, however, know the kind of readings to expect when the cable is sound and carrying a similar current, which can of course be determined experimentally.

The insulation resistance of high-tension mains varies regularly with the seasons, being highest in winter and lowest in summer.

A method of single-phase transmission suggested by E. J. Young (" Proc." of Am.I.E.E., *see* THE ELECTRICIAN, November 8, 1907) is interesting. It is probably intended primarily for overhead transmission, but might be useful for underground mains. A step-up transformer is used at the power station and a step-down transformer at the receiving end. If one transmission wire breaks down, arrangements are made for disconnecting this wire entirely at each end. The middle point of the high-tension windings of the transformers at each end are permanently earthed, and when one wire is disconnected the halves of the high-tension windings (normally

in series) are put in parallel. The sound line and earth now
represent the two conductors, with half normal voltage between
them, but full secondary voltage on both transformers. Fig. 125
shows this condition.

There is an arrangement known as " inductive balancing "
which can be made to limit the earth current in a faulty main
or automatically to cut it out of circuit. To illustrate the
principle, suppose the mains on a single-phase system supply-
ing a sub-station consist of two cables connected in parallel
with a common earthed return. The two mains are connected
to the same pole of the generator at the station, but are joined
together through an inductive winding at the sub-station end.
The middle point of this winding is connected to one end of
the transformer coil. Both mains being similar take equal
currents, which, flowing in opposite directions through the
winding, cause the inductive effects of each to balance each
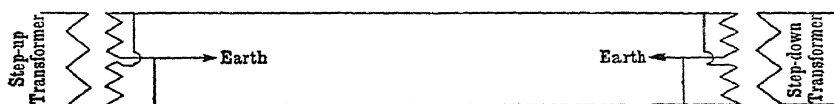
Fig. 125.

other, so that the resistance of the winding is all that counts,
and this may be made quite small. Suppose, now, a fault
occurs on one main, the currents in the winding will no longer
balance, and the inductive effect produced in the winding
may be made to work a relay, which disconnects the faulty
main at the sub-station end. If the main be disconnected
at the station the fault may now be located and repaired
without any dislocation of the supply. If the out-of-balance
effect is not made to cut off the main, it is still very useful,
because it greatly increases the impedance to any current
supply from the sound feeder to the fault. If the faulty
feeder is disconnected at the station, the fault current is limited
to a definite amount.

A modification of this principle may be made automatically
to cut out any faulty section of a ring main, and can be applied
to many other cases. It was first applied and described by
Mr. Leonard Andrews.

A method of automatically disconnecting a faulty high-tension feeder has been designed by Messrs. Merz & Price, and is in use on the Durham power schemes. A pilot cable is run alongside the feeder, and is connected through a relay coil and the secondary of a transformer at both ends to earth. The primaries of the transformers consist of a single turn of the main feeder. The secondaries of the transformers are connected in opposition to each other, so that if the current that leaves the feeder is equal to the current entering it, there is no resultant E.M.F. in the pilot wire and no current. If, however, a fault develops on the feeder, the currents passing through the two transformers will be different, and a local current will flow in the pilot, which, passing through the relay coils, causes these to close local circuits which trip out circuit breakers in the main feeder, thus isolating it at both ends. This arrangement may be applied to successive sections of a ring main, and affords a very complete protection ; it may also be used for a three-phase main, a three-core cable being used, and a transformer in each phase of the feeder. The fault may be fed by approximately equal currents from each end of the feeder, but then the transformers would no longer be in opposition and would thus still isolate the feeder.

The Merz-Hunter Split Conductor System.

The last method is now largely superseded by what is known as the split conductor protective system, which attains the same object as the Merz-Price system without the use of pilot wires. The operation of the system depends on the principle that two similar conductors of equal length, when connected in parallel at their ends, carry equal currents. Taking advantage of this fact, each core of a feeder is divided into equal conductors, these being arranged either as in a twin cable or as a concentric, but only lightly insulated from each other, and connected together at each end through a device which operates the switch should the currents in the two conductors become unequal.

The two conductors of each core are taken through the iron circuit of a current transformer, so that their currents tend to produce fluxes in opposition. As soon as a fault occurs, the currents become unequal, a resultant flux is produced in the

core, and a secondary winding on the core becomes energised and operates the relays controlling the switch.

It will be obvious that if the impedance of the two conductors of the split core differs, the currents will not be precisely equal in each split, and such difference will be largest when the current passing through the feeder is a maximum. The setting of the relay must, therefore, not be less than the difference of current which will occur with the largest possible current that can pass through the feeder while it is sound.

In practice, this difference of current in the split conductors is remarkably small, being frequently less than one-tenth of 1 per cent. of the total current passing through the feeder, always provided that care has been exercised in the manufacture and jointing of the cable. The question as to whether the cable should be a twin or concentric is decided as follows :—

The concentric method has the advantage that the larger over-all size of the core, due to the insulation between the splits, results in a reduction of the potential stress on the main insulation. perhaps an advantage of importance in the case of cables for working pressures of 20,000 volts and over ; on the other hand, it does not lend itself to jointing so readily. For pressures of 10,000 volts and under, and more particularly where any tee joints are likely to be taken off, the use of the twin type is advisable. In practice it is usual to cross the split conductors at joints to ensure absolutely equal impedances in each " split." So long as each conductor consists of equal lengths of inner and outer (concentric type) the precise number of cross-over joints is immaterial. For example, no difference can be detected in the working of the cable with one cross-over in the middle of the cable, as compared with crossing over at every joint. The impedances of the " splits " of a well-made cable are so nearly equal as to make it doubtful if crossing is really necessary, but since engineers with an extensive experi ence of the system *do* cross the joints this precaution is probably advisable.

The system may be tested by connecting a milliammeter in the secondary of the current transformer and noting the out-of-balance when the feeder is loaded. Probably the ammeter will not deflect, and the secondary winding should then be tested for continuity. This system is in use all over the N.E. coast 20,000 and 11,000-volt mains, underground and overhead.

In the Bowden-Thompson patent system the cable (say, a three-core E.H.T.) is built with insulated metallic shields between the conductors and between conductors and lead. These shields are connected to earth through a relay, which operates the main switch by means of a trip coil.

Any external damage to the cable earths the outer shield before the conductors are affected and operates the trip coil by means of a battery in the relay circuit. Similarly any leakage from a conductor causes an earth through a shield and operates the relay.

Among the advantages claimed for this system are :—

Rapidity of action and isolating a cable before complete breakdown ; provides protection between phases as well as to earth ; independent of fluctuations in supply pressure ; suitable for protecting any combination of feeders ; no tendency to cut off sound feeders under any conditions ; operates on an incipient fault ; special switchgear not necessary ; no pilot cables to lay or maintain.

In the opinion of the authors, the effect of the metallic shield between conductors will be to raise the stress in the dielectric very considerably, perhaps, by some 70 per cent. A bad contact or accidental disconnection in the small leads belonging to the protective system is not indicated. Experience has shown that it is better for an open circuit to operate the gear, thus drawing attention to its faulty condition. With regard to incipient faults, it is a common practice to keep a cable in commission until a fault becomes fairly developed in order that there may be the least delay in localising it. It is very probable that some faults would burn out the whole of the apparatus. Owing to the number of conductors in the cable, the joint-box fittings on the Bowden-Thompson system are complicated.

The *Callender-Waters* system of feeder protection involves the insertion in the cable of a special length, having a lower factor of safety than the remainder, which would breakdown and relieve a surge pressure, or, alternatively, a cable may be used having a high dielectric loss, which, it is claimed, tends to relieve surge pressures. This seems to be the same idea applied to cables, as is used on overhead lines, where corona

discharge is used as a safety valve.* The idea is ingenious and, if it can be practically applied, should afford a very useful protection against abnormal pressure rises. It is claimed in the patent specification that *cracked* oils used for impregnating the paper give the desired result.

Earths on Three-Phase Systems.

The B.O.T. regulation is : " When there is no neutral conductor, the neutral point of the high-pressure mains will be connected to earth at the generating station, but insulated from earth at all other parts. Where there are neutral conductors they will be connected to earth at one point only. In the case of the high-pressure mains, they will be connected with earth at the generating station."

A similar regulation applies to two-phase systems.

In practice, on a three-phase system the neutral point is generally earthed through a resistance. By earthing the neutral point the potential between any phase and earth can never exceed $\dfrac{V}{\sqrt{3}}$, where V is the potential between any two phases. With the neutral point earthed, a fault on any phase causes a heavy current to flow, which may, however, be limited by the neutral resistance. With the neutral point not earthed, a fault does not immediately do any harm, but on a three-core cable the static discharge is certain to break down another phase, and then a violent short-circuit occurs. This must obviously be worse than a fault between one phase and an earthed neutral, since the voltage is $\sqrt{3}$ times as great.

If the neutral point of a three-phase system be not earthed, an electrostatic voltmeter connected between each phase and earth will give an indication of the state of the insulation ; if the insulation resistance of one phase is lower than that of the others, the voltmeter connected to that phase will read lower than the other two. Probably the normal readings of the three voltmeters will not be equal, hence a fault will be indicated by one voltmeter reading lower than normal and the other two higher than normal. This arrangement is not very sensitive on considerable networks, as the lowering of potential

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* *See* " Jour." I.E.E., Vol. XLVI., p. 572, Matthews and Wilkinson : " Any induced surges or other high-tension phenomena are thus automatically dissipated in the form of corona discharge between the wires, and the line acts as its own safety valve."

due to leakage is masked by the capacity of the cables. To increase the sensitiveness, Mr. M. B. Field* has suggested that an inductive resistance might be connected between each phase and earth to balance the capacity effects. A still less sensitive arrangement for three-phase lines with unearthed neutral consists in connecting a number of lamps in series between each phase and earth ; if a bad earth occurs on any phase the lamps connected to the other phases will light. If the neutral is earthed, a leakage indicator can be inserted in the earth connection.

A method used in Mexico, was described by N. Rowe (THE ELECTRICIAN, November 1, 1907, p. 101) as follows : " The transformers† were connected in star on the high-tension side, the centre of the star being earthed ; and, in order to detect instantly when there was an earth on the line, a series transformer was put into this earthed line, and the secondary leads carried to the switchboard, where an ammeter was connected to them. With this arrangement, when an insulator broke down or the power current followed the lightning over an insulator, the station operator could tell when there was an earth on the line ; and by shutting down at once he was able to prevent the burning off of the transmission line."

Mr. H. G. Stott, in a Paper read before an American Engineering Society (*see* THE ELECTRICIAN, November 9, 1906), recommends earthing the neutral point of the generators or (step-up) transformers through a resistance. He also recommends insulating the lead of the feeders, except at the station, where they should be bonded and earthed. In a particular case quoted, of a large system supplying sub-stations at 11,000 volts, the neutral connection has a resistance of 6 ohms and a carrying capacity of 1,000 amperes. This limits the fault current to 1,000 amperes, since the potential to earth of any phase is 6,300 volts. When an earth occurs, the oil switches, actuated by the overload relay, trip out quietly on the earthed feeder only, without disturbing the rest of the system. It is obvious that it would be difficult to attempt completely to insulate the lead in sections when using high potentials. A difficulty occurs in earthing each neutral point of several three-phase generators supplying common 'bus bars,

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* " Proc." I.E.E., Vol. XLI., p. 200.

† Apparently " step-up " at the generating station

owing to the heavy triple-frequency cross-currents which may flow in the earth connections, but it may be obviated by connecting the neutral point of one machine only to earth, or by connecting each machine to a common bar through an inductive winding, this bar being earthed either direct or through a resistance.

There is a certain similarity between a three-phase system and a three-wire continuous-current system ; but, since the latter system is used for transmitting energy over comparatively short distances in populous centres, the earth connection presents no difficulty, water supply pipes being generally used. The earth connection in the former case is more difficult, and its resistance is liable to vary considerably, both with the weather and through the action of leakage currents. If water can be found at a reasonable depth on sinking a well, then the bottom of the well is a good place for an earth plate. Some earth plates are buried but connected by a pipe with the surface, down which salt water can be poured. Carbon ends packed round the earth plate are sometimes used for lightning conductors.

The earth plate on a single-phase earth-return railway, estimated to have passed 7,500 ampere-hours, showed no appreciable corrosion (Mr. C. F. Jenkin, Section G, British Association, August 6, 1906).

The New York Edison Co., with about 200 miles of cables working at 6,000 and 11,000 volts, do not earth the neutral point. They put over each three-core cable an iron ring, on which is wound a coil. Since the neutral point is not earthed, an earth on one phase will not produce any wattful leakage current, but will alter the capacity or charging current on that phase. Normally the three-capacity currents balance each other, and there is no E.M.F induced in the coil ; but when there is an earth on the circuit, the balance is disturbed and a current is induced in the coil. This current is made to operate a relay device, which disconnects the main circuit (Mr. P. Torchio, Am.I.E E., October 11, 1907).

Probably different systems of distribution—overhead, underground or a combination—require different treatment ; but an earthed neutral point, with an adjustable resistance and an ammeter in series with it, would seem to be the best arrangement. For, whilst a fault with an unearthed neutral does not

immediately produce any leakage current, American experience shows that it nearly always results in a short-circuit

Mr. J. S. Peck* sums up the question of earthing or not earthing the neutral point as follows :—

Generators' supplying underground cables : Neutral earthed through resistance.

Generators supplying overhead circuits : Neutral generally not earthed.

Generators supplying through step-up transformers . Neutral always earthed.

High-voltage overhead lines : Neutral not earthed, transformers connected delta.

Low-voltage generator supplying distribution circuits : Earthing generally preferred.

Step-down transformer supplying distribution circuits : Neutral always earthed.

A complete account of the methods employed to locate faults on the high-tension underground mains of the Commonwealth Edison Co., Chicago, has been given by W. A. Durgin.† The faulty feeder being isolated, an arrangement is provided for short-circuiting the phases at both ends. The fault is first of all " analysed "—that is, simple tests are made to find out which phases are earthed, which are short-circuited, and if a break exists on any phase , also the fault resistances are measured, and the resistance of any loop that can be made with a sound and an earthed phase. Great importance is attached to thus finding out the exact conditions existing at the fault. If all fault resistances and inter-connections are greater than 100 ohms, a high pressure is applied to break down the fault sufficiently to allow 1 or 2 amperes to pass for several hours. Mr. Durgin finds that a current of 1 ampere continued for 5 or 10 minutes will produce a carbon path through the fault of less than 10 ohms resistance if the paper is dry. If it is wet 3 to 5 amperes are required for 10 minutes followed by 1 ampere for five minutes. A " predictive " test is next carried out, and this is a Murray or Varley loop test, or a slight modification of these. The fault is then finally located by means of a telephone and a coil of wire carried over the route of the cable.

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* " Journal " I.E.E., Vol. L., p. 160.

† For an abstract *see* THE ELECTRICIAN, Aug. 19, 1910.

The predictive test having narrowed the ground down to a few hundred yards, or probably much nearer, this latter test is quickly made. It is pointed out that currents travelling on the cable sheathing may obscure this test as carried out in the ordinary way, and advantage is taken of the fact of the three conductors of a three-phase cable being laid up *spirally* together to get over this difficulty In the ordinary way the search coil is held with one side parallel to the cable, and a current travelling along the sheathing alone produces a noise in the telephone, equally with a current in the conductor alone, or the resultant of two unequal currents in the conductor and sheathing.

If, now, the plane of the coil be held at right angles to the cable, no current flowing axially in the cable or sheathing will affect the telephone, but owing to the conductors being spirally put up, the fault current in the faulty phase will not be flowing axially, but will, with the return current in the sheath, form a magnetic field the axis of which will lie in a plane which is not at right angles to the cab'e, and hence will induce currents in the coil, when this 'atter is held at right angles to the cable There can thus be no ambiguity with sheathing currents ; the only current making the telephone hum being current flowing in the spiral conductor itself, and this must stop when the fault is reached. A continuous current of 8 or 10 amperes is used, interrupted from 50 to 100 times a m nute by any convenient arrangement. If the fault resistance is too high to pass so large a current, a maller one of from 0·4 to 0·2 ampere is passed through the fault from the secondary of an induction coil, the primary current being interrupted by a vibratory spring, which breaks contact about 200 times a second. In order to obtain a dist nctive signal, the primary circuit is further broken at irregular intervals by a cam switch driven by a small motor. The search coil is now used as before, and the signal is stated to be quite as distinct as that obtained with the lower resistance fault. Such a small current passing through the fault may be compaiable in magnitude with the charging current taken by the cable, and in order that this may not impair the accuracy of the test, the three cores are joined together at the testing end. The three spiral cores carrying approximately equal charging curents are, as far as their external magnetic effect is concerned, equivalent to a single straight core, and the effect of

this will be balanced by the charging current returning along the lead. So that at any point on the cable where charging currents alone are flowing complete silence may be obtained by holding the search coil parallel with the cable axis. The single conductor connection is used for faults below 10 ohms resistance and the three-core connection for faults of greater resistance than 10 ohms.

In the case of a fault having a high resistance, so that current can only be passed through it by employing a very high pressure, direct-current Wheatstone bridge tests cannot be applied. A method of locating such faults has been described by L. C. Nicholson.* The faulty cable and a sound one are joined together at both ends to form a loop, and one terminal of the high-tension side of a three-phase transformer is connected in series with an adjustable resistance to the faulty
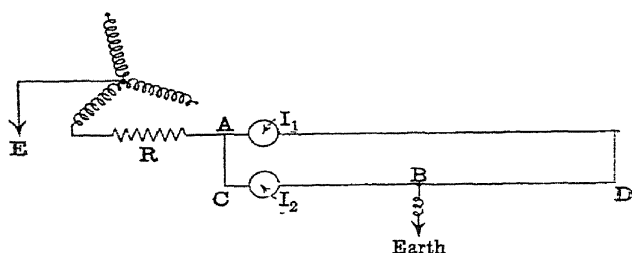
FIG. 126.

cable, the neutral point of the transformer being earthed. In each cable is an ammeter, and readings are taken on these instruments simultaneously.

Then if, in Fig. 126, r_1 be the resistance of ADB, and r_2 be the resistance from B to C, and I_1 and I_2 the currents shown on the two ammeters, we have the relation

$$\frac{I_2 - I_1}{I_2 + I_1} = \frac{\dfrac{r_1 - r_2}{2}}{\dfrac{r_1 + r_2}{2}}$$

$$= \frac{\text{resistance of BD}}{\text{resistance of CD}}.$$

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* *See* THE ELECTRICIAN, Nov. 15, 1907.

If the cross-sections of the wires forming the loop are not uniform a complication occurs, due to the different relative impedances of the two parts of the loop.

In some tests on a length of line of 118 miles the currents were, in the first case, 1·1 and 1·125 amperes, and in the second case 1 53 and 1·55 amperes. In the first case the location was wrong by 1,000 ft. and in the second by 200 ft. ; thus both were correct to well within 1 per cent. This method is used on an overhead line when the leakage takes place over an insulator, and it is not possible to lower the fault resistance.

Earthing in Mines—Leakage Indicators.

The Home Office Rules governing the use of electricity in mines require a leakage indicator to give a permanent indication of the state of the insulation of the system. If the system of supply be two-wire continuous current with both poles insulated from earth, a voltmeter connected between each pole and earth gives an indication of the state of the insulation, and the insulation resistance of each pole may be calculated from the formulæ

$$I+ = \left\{ \frac{v-(d_1+d_2)}{d_2} \right\} r \text{ ohms,}$$

$$I- = \left\{ \frac{v-(d_1+d_2)}{d_1} \right\} r \text{ ohms,}$$

where $\quad v =$ volts between positive and negative,

$d_1 = \quad$,, $\qquad$,, $\qquad$,, and earth,

$d_2 = \quad$,, $\qquad$,, negative $\qquad$,,

$r =$ resistance of voltmeter in ohms.

If one pole be permanently earthed, an ammeter in the earth connection will indicate the leakage current. The insulation resistance may be calculated as above by momentarily disconnecting the earth connection. Whilst we regard such calculations as of no practical use in large networks, it is very desirable to make them on small systems, where any fall in insulation resistance may be investigated.

On unearthed alternating systems, electrostatic voltmeters may be connected between each phase and earth, to indicate

the condition of the insulation, and if the neutral point of a
three-phase system be earthed, an ammeter in the earth
circuit will serve as an indicator, and, obviously, current flowing
in this connection may be made to operate a signal, as a bell,
or a relay circuit to cut off the supply.

Another arrangement that may be employed on either
earthed or unearthed alternating current systems is to super-
impose a small direct-current on the system. On an unearthed
three-phase supply, this may be arranged as in Fig 127, where
A is an ammeter, which is unaffected by alternating currents,
and R a very highly inductive coil of comparatively low
resistance. Any leakage from any part of the system is indi-
cated on the ammeter. Probably this arrangement would
not be very sensitive in some mines, if unarmoured and non-
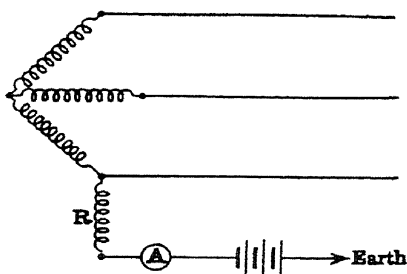
FIG. 127.

lead-sheathed cables were employed, as earthing is generally
a difficulty, and parts of some mines appear to be separated
from others by insulating strata. If the system is earthed,
the ammeter and cells are inserted in the earth connection, in
series with a fuse, which is shunted by a resistance ; in the
event of a bad fault, the fuse melts and the resistance limits
the fault current to an amount that wi l not injure the instru-
men . This device may also be made to close a local circuit
to operate the cut-outs in the main circuit.*

Automatic Cut-outs.

Automatic protective devices of various kinds are used,
and may be in the main and branch circuits, or in the neutral

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* A complete equipment for this arrangement, known as the " N.C.S."
leakage indicator is described in THE ELECTRICIAN, Jan. 14, 1910.

point earth connection. The former may be intended only to operate, when a small earth leakage occurs, or on overloads, or under both conditions.* In any case they are worked by current transformers, the primaries being in the main cables ; if intended to operate when an earth occurs, their action depends on the balancing of the currents in the three-phase cables, this balance being destroyed immediately any leakage current flows along one phase. Such devices may be arranged in series in a distributing system, with graded time setting, so that a fault occurring at the extreme end of a main, or in a branch, would operate the nearest cut-out, and so cut itself off before the cut-outs nearer the supply could work, the disturbance thus being confined to a small part of the mine only ; if the fault should occur near the supply end of the system, the maximum interference with working would result. Cut-outs worked by the leakage currents flowing in the earth connection necessarily cut off the whole supply, in the event of a leakage. An example of this class is installed at the Douglas Bank Colliery, Wigan. † A 7/16 earth cable is run from the power house to the bottom of the pit shaft (the shaft cables being unarmoured) where it is earthed and joined to the armouring of the distributing cables at each pit eye ; at the switchboard it is connected to one side of the cut-out device, the other side of this device being joined to the neutral points of the generators. The cut out consists of a pair of coils wound on a laminated iron core, which attracts an armature ; this closes a relay circuit which in turn closes a 230-volt circuit operating the coil tripping the circuit breakers in the shaft cables. It is claimed for this device that it can be made sensitive enough to operate when a person touches a live conductor down the pit. It is essential for the proper working of all such automatic cut-outs that a proper earth exists all along the cable route, and the best way to effect this is to use armoured cables throughout, and properly to enclose all "live" parts in ironwork, taking particular care to bond the armouring round, and on to, all fuse and switch boxes, &c. ; to use either flexible steel armouring for trailing cables, or a special earth wire made up with the cable, or bound to it, and to con-

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* *See* a Paper by E. B. Wedmore in THE ELECTRICIAN, May 6, 1910.

† Known as the " Winhey " detector.

nect this properly to all motor frames, &c.   So thoroughly is
the importance of the maintenance of the earth connection to
coal cutters, &c., recognised, that a system has been devised *
which includes the running of an auxiliary pilot cable in addi-
tion to the earth wire, from the gate end switch to the motor ;
this switch is controlled by a solenoid, the circuit of which is
completed by the pilot cable and the earth wire, *via* the motor,
so that if the earth connection is broken, the switch at once
opens, and cuts off the supply to the motor, and it cannot be
closed again until the earth connection is complete.   So long
as the armouring is metallically continuous all through the
mine, and connected to the neutral point and an earth plate
at the surface, it would not appear practically to be possible
for the armouring, or any metal connected to it, anywhere to
attain a dangerous potential above or below ground in its
vicinity.   For if N represents the neutral point of the gene-
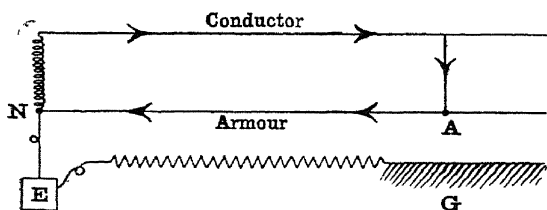
FIG. 128.

rator at the surface (in Fig. 128) connected to earth at E, and if
the armour becomes " alive " at A, due to a fault, then the
difference of potential between A and the ground at G could
never exceed the drop in volts along the armouring from A to
N, whether E and G were nearly insulated from each other, as
shown diagrammatically in the figure, or whether the resistance
between them were negligibly small.   If A and G were coupled
by an earth-plate there would be no potential difference
between them, but we should not regard earth-plates, which
are rarely reliable, as essential.   The armouring of any two or
more cables in the same road would be bonded together, so that
there could not exist any difference of potential between the
armouring of any two neighbouring cables due to two faults.
The drop of pressure along A N might, with alternating cur-

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* By H. J. Fisher, *see* " Proc." I.E.E., Vol. XLIV., page 664.

rents* be rather high, if A N were very long, but since it will be bonded to other cables, actually the drop in pressure can never be dangerous ; its magnitude depends on the amount of earth current flowing, and hence on the setting of the circuit breakers. If the cables were lead covered as well as armoured, the drop would be considerably reduced. Concentric cables are the safest as regards shock in all circumstances, and are also the class of cable least likely to fail. The protective action of the armouring on a three-core bitumen cable is magnified three times on an armoured lead-sheathed concentric cable, with the outer conductor earthed. If the cables are regularly tested, ample warning is given of any fault before it develops into a short circuit, unless it be caused by some mechanical force which cuts through armour, lead, and outer conductor to the inner immediately, in which case a short circuit occurs which will bring out the overload circuit breakers, and these conditions are precisely those in which they are desired to operate.

Locating Faults in Mines.

Faults in mines are generally located by testing circuits separately from a distributing board, and the faulty circuit
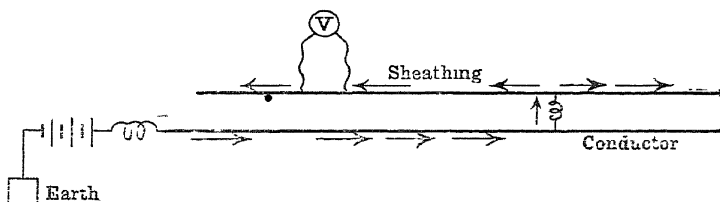
Fig. 129.

being found, an inspection of the cables will often reveal the fault. Bridge tests can be made with armoured cables, and an inductive method, such as a search coil and telephone, used when they are unarmoured. If the cables are accessible and lead covered, and the fault of low resistance, it may sometimes be found by determining the direction of the current in the sheathing when a continuous current is passed through the fault. This may be done by connecting a milli-voltmeter

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* On a particular steel tape armoured cable, we found the impedance, with a frequency of 50, to be roughly three times the ohmic resistance.

to points a few yards apart on the sheathing, the point where the current changes in direction, or ceases, indicating the fault.   (*See* Fig. 129.)

Earthing the Neutral Point of Three-Phase Systems.

Some difference of opinion exists as to the advisability of earthing the neutral point on a three-phase mining installarion, but the majority of British engineers are in favour of *earthing*. The factor of safety against disruptive breakdown is so high in modern cables designed for medium pressures that the question of whether the maximum possible strain on the insulation is 1,000 volts more or less with either system would appear to be quite unimportant, as far as the cables are concerned.

1. If the neutral point be earthed a fault is immediately indicated and must receive prompt attention, whereas if the neutral be not earthed a fault on one phase may be left until a convenient time for repairs ; the system is in a dangerous state during this period.

2. With an earthed neutral, a faulty cable can be made to disconnect itself automatically with certainty.

3. For the foregoing conditions to apply, the cables must be armoured or lead covered, or both, and the sheathing must be electrically continuous, and it must be earthed ; these conditions greatly reduce the chances of dangerous shock and of explosions. The chance of a shock from a fault is entirely absent, if the conditions as to armouring are observed : the character of the shock to an " earthed " person handling intentionally exposed " live " parts such as fuses would certainly be more severe with the earthed system, but the danger of doing so would be fully realised, and thus ought to be non-existent. With a small unearthed system " live " parts might be handled with impunity, so long as the whole installation was sound, but with a fault on one phase, a person might touch some " live " part on another phase without realising his danger. With armoured cables and enclosed fittings, no con tinuous arcing could take place, and practically no arc exterior to the armouring, unless the cable was literally torn asunder. With an insulated system, arcing might continue at a fault for long periods, since the whole system would be alternately charged and discharged through the fault.

4. The possibility of very high potentials between line and earth, caused by surges, &c., is nullified, if the neutral point be earthed.

5. A fault will probably be more quickly located and repaired with an earthed neutral.

On the other hand, there is the possibility of continuing the supply with a fault on if the neutral be not earthed, but probably the danger of running with an unlocated fault on the system quite nullifies this advantage. Again, the additional cost of armouring may be considered a disadvantage with an earthed neutral, but in many pits this is essential as a mechanical protection whether the neutral be earthed or not.

The arguments for and against earthing the neutral in colliery installations are discussed by Mr. W. W. Wood in an I.E.E. Paper,* which together with the discussion, should be consulted. *See also* Mr. Peck's Paper, " Earthed versus Unearthed Neutrals."†

Earthing on Continuous-Current Tramway Systems.

Tramway systems with an uninsulated return must comply with certain B.O.T. regulations, as to earthing, testing, &c.

1. The negative pole of the generator must be earthed, and the earth connection must consist of two separate earth-plates, 20 ft. apart, and 6 ft. from any buried pipe, or a water-pipe may be used, not less than 3 in. inside diameter (with owner's consent).

The contact resistance between the two earth-plates must be such that an E.M.F. of 4 volts inserted in A B (*see* Fig. 130) will produce a current of at least 2 amperes. This test must be made monthly, and is conveniently carried out with two small accumulators and an ammeter. The earth-plates should be sunk 7 ft. or 8 ft. in the ground and may consist of scrap iron plates, bolted together and packed with coke ; a 3 in. drain pipe may connect each of them with the surface, down which a solution of soda can be poured occasionally. A water pipe is always better than earth-plates.

2. A recording ammeter, P, must be put in the earth connection, and the current flowing through P must not exceed

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* " Jour." I.E.E., Vol. XLV., p. 559.

† " Jour." I.E.E., Vol. L., p. 150.

2 amperes per mile of single track, or 5 per cent. of the total current output ; the resistance of P must not produce a greater drop than 1 volt with the maximum allowable current.   A voltmeter connected across a shunt is always used.

3. If a connection be made between the rails and any pipe in the ground at the station end ⋅ f the line, the current in this connection must be capable of being reversed.

> (1) If current flows *from* rail *to* pipe, by three Leclanché cells,
>
> (2) If current flows *to* rail *from* pipe, by one Leclanché cell,

that is, the rails must not be positive to any pipe by more than 4·5 volts, or negative to any pipe by more than 1·5 volt.
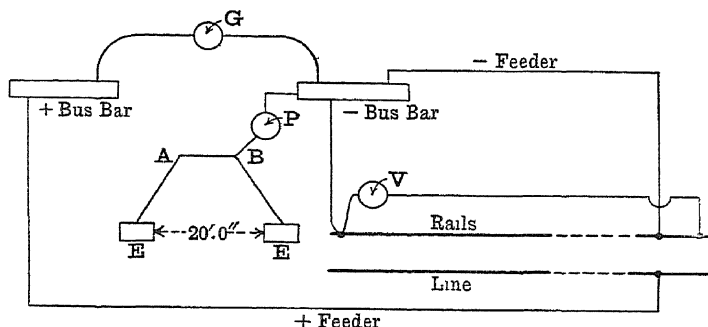
FIG. 130.—EARTHING ARRANGEMENTS OF CONTINUOUS CURRENT TRAMWAY SYSTEMS

4. The drop in pressure between any two points in the rails must be less than 7 volts, and a continuous record must be kept.   This regulation is observed by laying pilot cables to each terminus, and connecting them to a multiple way switch, so that any one can be connected to one terminal of a recording voltmeter (V), the other terminal being joined to the near end of the rails.

5. The leakage from the line must not be greater than $\frac{1}{1000}$th of an ampere per mile of tramway ; it must be measured once a week with the full working pressure on the line.   This test is made by inserting a low reading ammeter between the positive bus-bar and the line, the feeders being switched off, and no cars on the rails.

6. Insulated underground feeders must be tested monthly and must not test lower than 10 megohms per mile.

Artificial Earths.

Whilst we regard all artificial earths with great suspicion, and have frequently found them to be worse than useless, producing as they may, and frequently do, an entirely false feeling of security, nevertheless cases arise when they must be used. It is said* that experiments prove that an earth plate should be 18 in. square, made of cast iron not less than $\frac{1}{2}$ in. thick and buried in small coke. A 9 ft. cast-iron pipe, 3 in. diameter, buried in coke may also be used, but the Angus Smith solution should first be cleaned off it. We are of the opinion that earth plates should be tested at least yearly and probably more often.
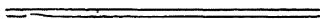
CHAPTER XI.

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CABLE AND JOINTING ACCESSORIES.

Jointing Compound and Bitumen.

The particular kind of compound selected depends to some extent on the use to which it is to be put. A large number of waxes are continually offered to electrical engineers as suitable for jointing purposes, and as these vary widely in price, it is important to be able to distinguish a suitable variety. Unfortunately, this is a difficult thing to do ; they are mostly very similar in appearance, and quite suitable compounds vary widely in physical properties such as melting point and specific gravity. Their electrical properties are nearly always good, the insulation resistance being of the order of two million ohms across opposite faces of a centimetre cube. The resistance to rupture is extremely high, one compound being stated to be able to stand a pressure equivalent to 50,000 volts per 0·1 in. of thickness. The chemical examination of such compounds is generally of little value, and indeed often meaningless to the engineer. For instance, of two compounds, both made by reliable people, the guaranteed analysis of one gives a little over 1 per cent. of ash and of the other 15 per cent. A brittle compound is liable to develop cracks if there should be any movement of the cable or joint box, whilst a soft compound may " age " and become porous. We believe the basis of many compounds is refined bitumen.

Bitumen. Specification of Properties.

Amongst clauses occurring in specifications for compounds and bitumen are the following :—

1. The material must be genuine Trinidad lake asphalt, combined with 8 per cent. heavy petroleum residuum.

2. Free from water, coal tar and coal tar derivatives.

3. Petroleum residuum shall not have a flash-point below 350°F., and heated for seven hours at 400°F. shall not volatilise more than 5 per cent. by weight.

4. Specific gravity to be about 1·3.

5. To contain 65 per cent. matter soluble in carbon bisulphide.

6. Neutral when tested for acids or alkalies.

7. Completely soluble in benzol.

8. Homogeneous.

9. Shall contain no resin nor linseed oil.

10. Shall consist of about 68 per cent. petrolene and about 31 per cent. asphaltene.

11. Melting point not less than 210°Fah.

Bitumen is a natural product, the chief course of supply being a lake of bitumen in Trinidad and the land in its near neighbourhood. The crude substance contains about 35 per cent. of mineral matter, consisting of an impalpable siliceous clay with some oxide of iron and about 2 per cent. of alkaline salts, all of which are objectionable as causing slow deterioration of the bitumen.* Its specific gravity varies from 0·95 to 1·5, depending on the amount of mineral matter present ; its melting point varies from 180°F. to 600°F. Purified bitumen extracted from the crude Trinidad bitumen softens at 169°F., flows at 181°F., its melting point is 220°F..† and its specific gravity 1·032. Petrolene is the name given to bitumen or to part of a bitumen soluble in petroleum ether, and asphaltene is that part insoluble in petroleum ether, but soluble in carbon bisulphide. Refined bitumen is purified bitumen as above, mixed with some petroleum residuum up to 15 per cent. or so to soften it. It should have the consistency of beeswax. Crude bitumen, clay, plaster of paris and siliceous matter may be added for cheapening purposes.†

The name pitch is applied indifferently to crude bitumen or to products of the destructive distillation of coal, but more particularly to the latter. Gas tar and its products contain " insoluble organic matter as a result of the high temperature to which they have been subjected, and the subsequent resulting decomposition has an injurious effect on insulating compositions."† We have never found pitch prepared from

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* Sutherland, " Bitumen in Insulating Compositions," ' Proc." of the Faraday Society. † *Ibid.*

coal to be completely soluble in benzol; there is always an insoluble part left, resembling coke when viewed under the microscope. The residue left on filtering a solution of bitumen in benzol is a brown powdery substance and is probably the mineral matter referred to above. In a recent police court case comprising a prosecution under the Merchandise Marks Act, the decision was given that a mixture of 30 per cent. flux (a residual product from shale oil), 40 per cent. manjak and 30 per cent. mineral matter could correctly be described as " Trinidad bitumen." Manjak is a substance containing 90 per cent. bitumen, obtained from Trinidad, but of the " Land " variety.

Joint Box Compound.   Specification of Properties.

1. Shall be non-hygroscopic.
2. Shall be homogeneous.
3. Shall contain 90 per cent. soluble matter.
4. Shall be completely soluble in benzol and leave no mineral residue.
5. Neutral when tested for acids and alkalies.
6. A slab 1 in. thick shall withstand 35,000 volts alternating pressure.
7. Insulation resistance, measured after above pressure test, at 500 volts, must be 250,000 megohms.
8. 78 per cent. soluble in carbon bisulphide.
9. Specific gravity 1·2, 1·08, 0·99, 1·25 and 1·09.
10. Must have high melting point.
11. Melting point to be about 200°Fah.
12. To contain 99 per cent. pure bituminous matter.
13. Must have no injurious action on iron, lead, or insulating materials.
14. Unaffected by water, acids or gases of any kind.*
15. Shall contain no sulphur.

The above clauses are given at some length to show the diversity of opinion on the properties of box compounds.

We should regard the following as desirable points in a jointing compound :—

(*a*) It must not be so brittle as to be readily chipped, and it must not be easily cut with a knife ; but it must be a very tenacious and sticky substance, capable when heated of being

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* Coal gas attacks most of these compounds.

drawn out into long threads, and of adhering closely to metals and insulating materials.

(*b*) It should be able to be poured at from 200°F. to 210°F.

(*c*) Melting point (requires special definition in a specification) should be about 200°F.

(*d*) It should be completely soluble in benzol, and no residue should remain on the paper after filtering the solution.

(*e*) A layer about 0·1 in. thick should lose less than 1 per cent. by weight after 20 days' heating at or near its melting point.

(*f*) A cable end placed in a wooden box, should be sealed with the compound and placed for 20 days in a solution of salt and water, the conductor being maintained at a continuous potential of 500 volts below the solution. At the end of 20 days the insulation resistance must be the same as at the beginning.

Regarding (*a*), (*b*) and (*c*) of the above, it may be said that some engineers prefer a hard, high melting point compound for filling boxes, but we do not think there is any advantage in using such a compound over the kind indicated above, (*d*) is designed to prevent the compound being loaded with mineral matter, (*e*) gives some indication of the stability and permanence of the compound. Fig. 131 shows the results obtained with this test on some sample compounds. The samples were melted and poured into shallow metal trays, so as to cover the bottom completely, and the trays were of equal size so that the same surface was exposed in each case. These were placed on a shelf in a large biscuit tin, and underneath the shelf an old 32 c.p. incandescent lamp was burned. With the lid on and some adjustment of holes in the top and bottom, a constant temperature of 200°F. was obtained. The samples were weighed at intervals ; all those shown in the figure, except Nos. 5 and 6, cracked badly on cooling down to be weighed. Nos. 1 and 6 had the lowest melting points, and Nos. 3 and 4 the highest ; No. 3 was not a pure bitumen, the curve for which is more like No. 5, which is itself especially noteworthy. No. 6 was kept in longer than is shown in the figure, and the curve became practically horizontal at 25 days, the total loss being still well under 1 per cent. We should regard Nos. 5 and 6 as suitable, Nos. 4 and 3 as doubtful, and Nos. 1 and 2

as quite unsuitable. Probably the surface only of the compounds with the higher melting points was affected, whereas, owing to diffusion, the whole bulk of No. 6 would be affected. The biscuit tin mentioned above is useful for measuring melting points, as a wide range of temperatures can be obtained.

The last test (f) is essentially practical and measures the tendency of moisture to creep between the compound and lead
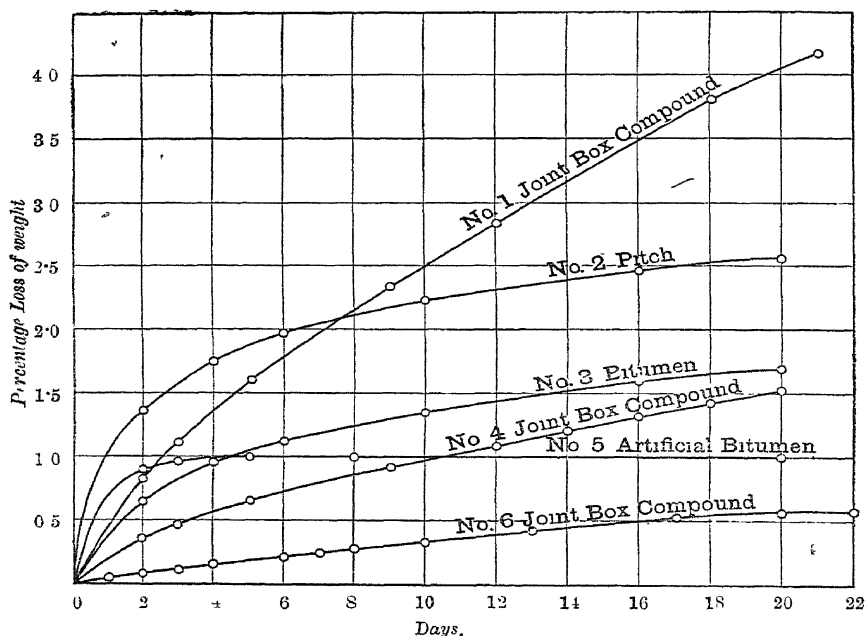
Fig. 131.—Curves showing Loss of Weight of Compounds subjected to a temperature of 200°F.

sheathing of a cable, or the adhesiveness of the compound ; most samples will withstand this test, which may be made more severe by using an alkaline liquid.

Paraffin and ozokerite wax and other similar substances are added to some compounds. Paraffin wax has been tried by itself for filling joint boxes, but it shrinks and becomes porous with age, admitting water to the fittings. Another point to notice in a good box compound is that it should not shrink

excessively on solidifying ; and, in any case, room for expansion should be allowed for the compound, in dividing boxes, &c., especially in sub-stations and places likely to get hot.

Joint-box Compounds.

It is desirable that a joint-box compound should be " tacky," or of a rubber-like consistency at ordinary temperatures, thus reducing the tendency of the compound to crack.

The basis of a well-known compound is stated to be " a rubber-like asphaltum."

Care should be exercised by the jointer that the compound is not over-heated. It is sometimes recommended that a thermometer should be used, but we do not consider this necessary as a rule. Crackling and frothing during heating indicates the presence of water, and if this occurs the compound must be heated, with constant stirring, until all frothing ceases.

For extra high tension work the dielectric strength of the compound used becomes of importance It is not generally known that this varies enormously with the temperature , Fig. 132 *A* shows the relation between dielectric strength and temperature of a high-class joint box compound. Several other compounds which we have tested, including a resin-oil mixture, give a curve of the same shape. The dielectric strength begins to drop rapidly as soon as the compound begins to get liquid ; when completely liquefied any further rise in temperature has only a small effect

This point is obviously of importance in connection with compounds which have to be used in hot countries, or in substations, &c., where the temperature is likely to be high. The strength of the compound in Fig. 132 *A* is calculated from breakdown tests between spheres. The breakdown between needle points is widely different from that between spheres, and the element of time enters largely into the question, because energy is dissipated in the compound at the needle points. This raises the temperature, and thus reduces the dielectric strength. For example, a compound which broke down between needle points at 38 kilovolts, when the pressure was raised quickly, broke down under a pressure of 25 kilovolts after one hour's steady application, and would very likely have failed at a lower pressure if it had been

maintained for a longer period, but no similar effect could be detected with spheres. The importance of avoiding anything in the nature of points in a joint will be obvious.

The relation between insulation resistance and temperature, of the same compound, is shown in Fig. 132 *B*, the tests being made between spheres. Galvanometer deflections taken at the end of one minute are plotted, and these are, of course, inversely as the insulation resistance. Finally, the dielectric coefficient of the compound becomes of importance in the design of a high-tension joint, in order to guard against an
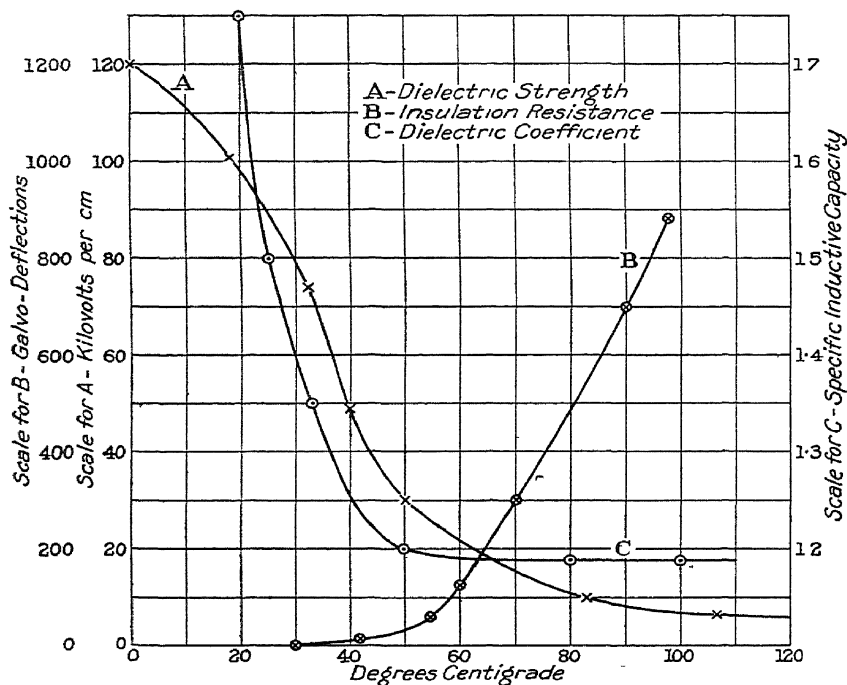
FIG. 132.—JOINT BOX COMPOUND.

unequal distribution of stress. This again varies with the temperature, probably because the density alters; Fig. 132 *C* shows the relation for the same compound as the other two curves

It will be seen from this figure that all three curves follow approximately the same law, and that during liquefaction of

the compound, which at normal temperature is of a rubber-like consistency, the dielectric strength, insulation resistance, and specific inductive capacity, all fall rapidly tending to reach constant values when the compound is completely liquid.

Concerning the theoretical significance of these curves the following quotation from " The Electrician " (Nov. 18, 1910), translated from the "Comptes Rendus," is of interest:—

" Pure vaseline, which is an insulator at ordinary temperatures, and a conductor when in the liquid state, acts as a medium charged with free ions of opposite signs, whose mobility which is nothing when the substance is semi-fluid, is only indicated when liquid portions appear."

Insulating Oils.

Oil is used for filling joint boxes, for making paper insulated cable joints, for immersing fuses, switches and automatic cut-outs, and for cooling transformers.

For jointing work resin oil is commonly used, and sometimes for fuses and switches ; it was formerly used for transformers, but now a mineral oil is largely employed for the purpose.

Resin oil varies a good deal in appearance, as obtained from different firms, largely owing to different resins being used for distilling. It may be dark brown and viscous or a bright golden comparatively thin oil, with all intermediate grades. A fairly thick oil is used for jointing work, in which the jointing tapes are boiled, and a thick oil must also be used for filling boxes, otherwise it will escape into the cables. Some jute insulated cables were jointed in iron boxes, which were filled with oil, and when examined two or three years later the boxes were found to be nearly dry. The oil may be thickened to any desired extent by dissolving resin in it ∗ Resin oil should always be heated to a temperature above 212°F. before using to drive out any moisture that may be present , paper or jute insulation from a cable suspected to contain water, may be tested by immersion in resin oil or paraffin wax heated to 220°F. in a glass beaker, when minute bubbles may be seen rising if moisture is present. Resin oil should

If sufficient resin be added, the compound will be solid when cool. Clean resin must be used ; it should be completely soluble in warm alcohol. The dielectric strength increases with the resin content.

not be relied upon as a water shield, because dirty water, in particular if slightly alkaline, chemically combines with it, forming a greasy substance which has a very low insulation resistance and dielectric strength; hence, joint boxes filled with resin oil must be water tight, and there should be no access of damp air to switches or fuses immersed in it. If exposed to the air for long periods it tends to become gummy, and this tendency is the greater the less refined the oil is.

On breaking a circuit under oil, a bubble of hydrogen rises to the surface, leaving a filmy trail of very fine carbon particles in its path. In time the oil becomes quite black, due to this carbonisation. We could detect no fall in the insulation resistance of a resin oil, in which a 10-ampere continuous arc lamp circuit was broken over 200 times and which had become quite black; the dielectric strength * is, however, lowered, and it is possible that when the carbon settles on the bottom, which, in the case of resin oil, takes a very long time, a conducting film might be formed. On breaking an alternating current under oil, the same phenomena occur, except that the arc is smaller, and cannot be maintained as the continuous arc may, and the carbon deposit is rather less. The oil used in switches must on this account be periodically changed.

For transformers a pure mineral oil derived from petroleum is used. It should have a light clear colour, a neutral reaction, be free from water and sulphur compounds, have a high flash point (180°C.), a high dielectric strength, a high insulation resistance, and be non-volatile, and should not deposit any solid matter or sludge when heated to 150°C. in the presence of metallic copper and air passed through the oil. For switches, the oil should be more viscous than that used for transformers, being in the latter case intended to circulate freely. Most of these points are fairly easily tested; its neutrality is tested by warming a sample with distilled water and alcohol (itself previously tested), allowing the oil and water to cool and separate, and testing the water solution when cold with phenol phthalein as an indicator. The solution is then titrated with $\frac{N}{10}$ sodium hydrate, the indicator turning pink immediately

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* The dielectric strength is said to rise at first, but begins to fall as the carbon in suspension gets thicker. The dielectric strength increases with temperature whilst the insulation resistance falls.

the acid is completely neutralised. The presence of water will be indicated by shaking the oil in a test-tube with exsiccated copper sulphate, which will assume a bluish tinge if water is present. A considerable quantity of water present is shown by the turbid appearance of the oil. *The flash point* is measured accurately in a special apparatus, such as the Pensky-Marten tester or Gray's tester, in which the oil is slowly heated in a partially closed vessel, and when inflammable gas is being given off, a flash is obtained on applying a light ; an approximation to the flash point may be obtained by using a home-made arrangement. The *dielectric strength* and the *insulation resistance* are both a measure of the purity of the oil, but facilities may not always be present for testing the dielectric strength ; the method of carrying out the test should be defined in the specification, and the temperature at which both these tests are to be made should also be stated. *Viscosity* is measured in a viscometer by observing the length of time a definite quantity of oil, at a definite temperature takes to flow through a small hole as compared with water or rape seed oil as a standard The specific viscosity is the ratio of the times taken by equal volumes of the oil and the standard respectively, to flow through the same hole. The standard instrument has a hole 0·067 in. in diameter ; an apparatus can easily be arranged to give an approximate figure. The *volatility* is measured by determining the loss in weight of a sample after heating at a definite temperature, for a definite time , for example, after heating at 100°C. for eight hours, the loss should not exceed 2 per cent. to 3 per cent. *The specific gravity* is measured, approximately with a hydrometer or more exactly, in a specific gravity bottle.

Dust and moisture should be carefully excluded from the transformer case, and rubber leads should not be used in the oil. The transformer should also be *designed* to work in oil, otherwise the oil may dissolve out shellac and other materials from the coils.* The oil should be heated up to 100°C. before use, to drive out any moisture that may be present.

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* For an account of transformer oil *see* a Paper by Digby and Mellis, " Proc." I.E.E., Vol. XLV., page 165.

Jointing Tapes.

The chief tapes for non-hygroscopic insulation are rubber, vulcanised bitumen, and prepared tapes, used for vulcanised joints. These latter are rarely employed now, as rubber cables are seldom installed for underground work. Pure rubber tape is chiefly used for temporary work and for exposed cable ends on inside connections. Bitumen lapping, also known as Bitite, is used for insulating joints on vulcanised bitumen and lead-covered cables (*see* Part II., Chap. XII.). It is made in different qualities and used w th hot compound ; inferior qualities will split if the compound is a little too hot, whilst the better and more expensive kinds will stand a very considerable heat. One way to test the quality is to make a joint with it, purposely overheating the wax ; the best quality should not crack or split when the hot wax is painted on.

Strong unsized linen tape, which is boiled in oil before use, is employed for joints which are to be enclosed in a lead box or otherwise protected from moisture. Protective and so-called water-proof tapes are of many kinds ; the most durable is a very strong tape impregnated with ozokerite of a low melting point ; this is rendered very sticky and adhesive before using by warming it, and is used as a protective covering for the bitite lapping mentioned above Any prepared tape with claims to be water-proof should show no white or light-coloured threads on being torn across ; every fibre should be thoroughly impregnated. Such tapes as are coated on the outsides only are merely of use for temporary connections and should not be used on permanent work of any kind.

Solder and Plumbing Metal.

The solder used for jointing should be half tin and half lead, whilst plumbing metal for lead wiped joints should be made up of two parts lead to one part of tin. A small piece of bismuth added reduces the working temperature, and may be used for such work as sweating lead-tin alloy fuses into terminal lugs, or on to copper. If less tin is used in the plumbing mixture, the joint may be porous.

Resin is generally used as a flux for electrical work. Many materials are in common use as soldering fluxes, *e.g.*, tallow,

resin, killed spirit (a solution of zinc chloride in an excess of hydrochloric acid), tin chloride, ammonium chloride (sal ammoniac), glycerine, stearine, either singly or in admixture. The most popular are those which contain the chlorides of zinc, tin, or ammonium.   *All fluxes which contain these ingredients are corrosive in the presence of moisture,* and all act owing to the development of hydrochloric acid when heated, the hydrochloric acid being one product of the decomposition of these salts by heat.   The hydrochloric acid so liberated attacks the oxide on the surfaces to be soldered and removes it by conversion into the chloride, which is subsequently volatilised or floats upon the surface of the molten solder, solidifying to a glass like bead upon cooling.   It might here be pointed out that for brazing and hard soldering, fluxes such as borax and sodium phosphate are used, which act, not by generating an acid, but by dissolving the oxides in the molten flux.   These fluxes require a fairly high temperature for fusion, and hence cannot be used for soft soldering.   Fluxes containing the above mentioned corrosive agents can be used to make joints which are not liable to corrode, but extreme care is necessary, the smallest quantity of flux must be used, and the whole of the flux on the joint must be heated so as to volatilise the corrosive ingredient. No unheated flux must be allowed to remain upon the metal away from the joint—an extremely difficult result to attain when dealing with stranded cables.   A suitable solder for aluminium is stated to consist of zinc 21 parts, tin 76 parts, and aluminium 3 parts.   Soldered aluminium joints are liable to deteriorate with age, and an apparently sound joint when new may go wrong in two or three months.   The surfaces of the conductors to be joined should be scraped whilst covered with the liquid solder.   Probably mechanical joints are always better for aluminium.

Rubber Gloves.

These should be carefully tested before being issued, and at frequent intervals.   They can be tested by suspending them, by means of clips from a string, in a pail of salt and water and filling the interior of the gloves with the same solution. For use on a 2,000-volt circuit a potential of 4,000 volts alternating is applied between the solution inside and outside the

gloves for 15 minutes, copper wires being used for electrodes. Those that fail usually break down within a few seconds from switching on, much more rarely within two or three minutes ; but out of a large number we have tested, we have not known one to fail after the first five minutes. A light fuse is put in circuit to protect the transformer. Probably the voltage is in excess of 4,000 at the moment of switching on.

Castings for Cable Fittings.

These are made of gunmetal or brass of high quality, but the conductivity of either of these alloys is at the best only a small percentage of that of pure copper. Fittings are rarely made of copper without the admixture of tin or zinc on account of the difficulties in casting the pure metal, which can only be overcome by using pressure. An alloy of 90 per cent. Cu and 10 per cent. Zn furnishes good clean castings which are tough and strong. The effect of adding different proportions of Zn and Sn to copper is shown in the following table :—

	Alloy.	Per cent. conductivity compared to pure copper.
1.	96% Cu, 4% Sn	27·8%
2.	94% Cu, 6% Sn	18·5%
3.	92% Cu, 8% Sn	11·2%
4.	97% Cu, 3% brass	44·4%
5.	94% Cu, 6% brass	46·5%
6.	99% Cu, 1% silicon copper	50·0% about
7.	99·8% Cu, 0·2% Mg	over 60·0% (?)

Copper alloys are liable to be patchy in composition, and the conductivity depends to some extent on the treatment, such as the time of cooling. The conductivity of the joint fittings cannot be expected to be greater than about 40 per cent. of that of pure copper. This is not usually a matter of great importance, on account of the relatively small proportion of the length of a cable in which the conductors are replaced by box fittings. Concentric and triple concentric cables are the only types in which any of the conductors are replaced by fittings in the service boxes. Where services are numerous, an allowance must be made for the increase in resistance caused by the box fittings, when estimating the drop in the main. In disconnecting box fittings and links the current density should not exceed the limits stated below. The main features of importance in designing fittings are :

1. Provision of sufficient section of metal to keep the current density down to 500–1,000 amperes per square inch

2. Castings to be of uniform texture, *i.e.*, thoroughly alloyed, so that they are strong and tough.

3. Provision of true contact surfaces, where parts of the fittings are clamped together, and of such an area that the current density through the surfaces does not exceed 250 amperes per square inch

Fuses.

These are accessories of the highest importance to the mains engineer, as they are used at numerous points throughout the system, for the protection of the cables and other apparatus against overloads.

The general specification of the fuses themselves depends on the following conditions. They must be capable of carrying the normal loads with safety, and must break the circuit with certainty when a given overload is applied, such as that due to a " fault " current. They must also withstand the results of a short circuit on any of the cables they are designed to protect.* They usually have to operate in a limited space, and must therefore melt cleanly and quietly without permitting the arc to spread to other conductors, or to the containing box itself.

The rise in pressure and current due to the breaking of a short circuit on an ordinary open fuse may reach enormous figures. For example, the pressure may reach 800 volts on melting a 40-ampere fuse on a 100-volt circuit † To minimise this explosive transformation of energy it is necessary with an open fuse to have a long break and to draw out the arc, but this is very inconvenient in network boxes and pillars. In these it is preferable to employ enclosed fuses of the Mordey or dust type, as they do not permit of the dangerous dispersal of molten metal, this being cooled and absorbed by the filling powder

One of the chief advantages of the " enclosed " fuse is that it is designed and rated for a definite value of fusing current, and it may be relied upon to act within a few per cent. of its

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* *I.e.*, melt without explosive violence.

† *See* Schwartz and James, " Proc " Inst.E.E., Vol. XXXV., No. 174.

rating. The centres for holding down nuts are fixed once for all, and can be made different for differently rated loads, and thus prevent the improper replacement of a " blown " fuse. The terminals also have more satisfactory contacts than that of an ordinary wire or strip screwed down under a nut. Although the whole current is not carried by the enclosed fuse, the copper element in the composite arrangement of copper and tin, as described below, should be of the enclosed type.

The successful use of open fuses of any of the materials, on which notes are appended, is mainly a question of the length of break and the design of fuse carriers and insulating fillets which will limit the effects of the arc, and the dispersal of, melted fuse metal. Other things being equal, a small volume of metal in a fuse is a very desirable feature.

The results of some experiments on the melting of heavy fuses on continuous-current short circuits showed that, of all the different types tried, oil fuses were the most violently explosive, and, as previously pointed out, this type of fuse should be used only on alternating-current circuits.

Tin and Copper Combination.—A fuse consisting of a combination of tin and copper, in parallel, the latter being of the Mordey type, behaves very satisfactorily. The tin which is not enclosed and which carries most of the current, being short-circuited by the copper at the instant of blowing, melts quite quietly, with no spluttering, and the copper melting immediately *afterwards*, being enclosed, does no damage. A possible objection to the use of tin, in exposed situations, is that below 20°C. it is in an unstable condition, and may change to the grey variety. The inductiveness of a circuit is, of course, a factor largely influencing the behaviour of any fuse on melting.

Copper Fuses.—Copper oxidises rapidly at a red heat, and copper fuses attain this temperature when carrying three-fourths of their fusing current. They also slowly deteriorate at a much lower temperature, but this may be partly prevented by tinning.

Tin and Lead.—Tin and lead, or an alloy of these two, are much more likely to hold an arc than copper, owing to their greater relative bulk, and hence the larger amount of molten metal and vapour. Some experiments made by the authors with pieces of paper arranged in a gap, shunting the fuse,

showed that there was a less rise of pressure with tin-lead alloy wires than with copper when " blown " on a short circuit, and that, although there was much more arcing and spluttering, there was less noise.

Aluminium.—Aluminium tested under the same conditions behaved something like copper, but was certainly less noisy; it is said to be unreliable, owing to the skin formed which holds up the molten metal, although this view is disputed, and in any case does not apply to heavy network fuses intended to melt only on short circuits. Aluminium fuses have been successfully used at Halifax, the contact ends being blackleaded to prevent electrolytic corrosion.*

Non-Arcing Metals.—Zinc with cadmium, bismuth, antimony and mercury form the so-called non-arcing metals. These metals have all low melting points, and a low counter E.M.F., and have the property of not maintaining an alternating-current arc, the un-ionised metal vapour being very highly insulating. Zinc strip melts very prettily on a moderate overload (200 per cent. about). It is sluggish in action, and hence has been suggested as useful for fusing arc lamp circuits, which take momentarily large currents at starting. The sluggishness is said to be due to the oxide or other skin formed. Of two fuses in series of the same metal, one heavier than the other, the heavy fuse appears only to melt, when the arc formed by the melting of the lighter fuse is very persistent. With alternating currents fuses behave more erratically than with continuous currents, and it is suggested that one reason for this is the loosening of the contacts by vibration.

Pilot Wire Fuses.—Pilot wires led back to the station from feeding points or from sub-stations are usually fused at the " live," or feeding-point, end. The most convenient and safest type of fuse is the Mordey, as enclosure is important in an underground box, on account of the possible presence of inflammable gases.

Fuses in Mines.—Fuses on mining circuits, if below ground, are usually in ironclad boxes, designed to be water tight and gas tight. In a good modern type, the fuses are in tubular porcelain holders, contained in a cast-iron box with a lid

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* W. M. Rogerson, The Electrician, Vol. LVIII., page 967.

bolted down on machined flanges $1\frac{1}{2}$ in. wide. The cables entering the box, if lead covered, are bonded to the box by means of lead bushes.

Fuses on Alternating High Tension Circuits.—On high-tension circuits, fuses are generally located in sub-stations, oil fuses being largely used ; there are two principal types, in one of which the fuse is completely immersed in oil, and in the other the ends are pulled under oil at the moment of melting.

For protecting isolated buried transformers a variety of the Mordey fuse has proved successful ; the particular type referred to consists of a very small copper wire enclosed in a glass tube, packed at each end with sand or inert material such as flue dust, leaving a clear space in the middle. The whole fuse fits into spring-clip contacts, and it is vary rare for the glass to be broken when the fuse blows. If a transformer is protected by fuses on the high and low tension sides, of equal kilowatt rating, the high-tension fuse always melts before the low tension. If there are three sets of fuses in series, the high and low-tension transformer fuses being of equal rating, and the consumer's service fuses of a much lower rating, the high-tension fuse is frequently the only one to melt, when a short circuit occurs on the consumer's wiring. This is probably due to the fact that copper is used on the high-tension side, and lead alloy on the low-tension side, and copper is more sensitive than any other metals. except brass and nickel.

" *Bates* " *and* " *Sparklet* " *Fuses.*—High-tension fuses are distinguished from low-tension mainly by the greater length of break, and the design of the carrier or holder. Besides the oil type mentioned above, the two varieties that are most used are (1) the " Bates " type, where the fuse is contained in a tubular handle open at each end, and (2) the " Partridge " or " sparklet " type.

The " Bates " type is satisfactory in action and safe to handle, owing to the hand-grip being external to the tubular fuse chamber. The air in the porcelain tube being heated by the arc set up when the fuse melts, rapidly expands, and blows the metal vapour out at each end, thus extinguishing itself. In the " Sparklet " type a small bomb of thin metal containing compressed CO_2 is placed in the porcelain holder, so that it is burst by the arc immediately it starts, and the large volume of gas thereupon liberated very effectively suppresses the arc.

For heavy high-tension sub-station feeders, the sparklet type is well adapted, while the smaller branches can be safely protected by the cheaper tubular type.

Sluggishness of Metals.—The relative sluggishness of various metals is given by Dr. G. J. Meyer as follows* —

Metal.	Relative sluggishness.	Melting point.	Relative mass.
Copper	1·0	1,054°C	1·00
Brass	0·47	about 1,015°C.	1·61
Nickel	0·362	about 1,400°C.	1·72
Aluminium	3·04	600°C.	3·08
40% lead—60% tin	3·1	135°C.	14·40
Lead	6·08	325°C.	20·25
Tin	7·0	230°C.	13 90
Zinc	7·60	412°C.	8·18

These figures are for long circular fuses, melting with the same current. Brass would appear to be suitable for house service fuses, to prevent the transformer fuse being melted, but it is said to be impossible to reproduce the alloy with uniformity, owing to segregation of the zinc. Nickel has a high melting point, and would thus, if rated to melt at 100 per cent. overload, be nearly red hot at full load, and is in this respect as objectionable as copper in small sizes and unenclosed. Perhaps zinc might be used in the Mordey carrier, on the high-tension side of a transformer, in place of copper ; its conductivity is rather less than one-third that of copper.

Of fuses in general it may be said that the rating depends on the position in space, the size of terminals, the enclosing case, ventilation, &c., so that it is best not to depend on other people's ratings, but to determine experimentally the rating of the fuses used, under service conditions.

CHAPTER XII.

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JOINTS, BOXES, DISCONNECTING BOXES AND PILLARS.

Joints and Jointing.

Joint boxes are essential on every cable system, for the purposes of coupling individual lengths of cable, and for jointing up branch circuits and service lines. Disconnecting boxes and pillars, with fuses or links, must also be provided in sufficient numbers, to control the general security of the supply and permit of periodical testing.

As has been already stated, few faults on the mains or stoppages of supply can be attributed to inherent defects in the cables themselves; on the other hand, every time the continuity of the insulation is broken for the insertion of a box of any kind, there is introduced a potential source of weakness. Jointing is, therefore, a department of mains work which demands great skill and close attention to every detail. The chief conditions which every cable box or joint should satisfy are : (1) It must have fittings of sufficient section and strength to carry the load current as safely as the original conductor, and (2) its introduction should not lower the insulation resistance of the cable. The second condition depends on the choice and application of the insulating materials used, and the design of the protecting box, with special reference to clearance for the fittings and, above all things, watertightness.

The number of types of cable now in use, and the diverse attempts to satisfy the conditions of jointing outlined above, have led to the introduction of an enormous variety of boxes, with which it is impossible here to deal even partially. What we propose, therefore, is to describe, firstly, the general principles to be observed in making any joint, taking as an example a straight or tee joint on a lead-covered cable, and from this proceed to give the special features of those that are more complex.

The details of apparently the simplest joint are worth considering at some length, as one sees very bad work done by

those who have only occasionally to undertake it, and consequently do not appreciate its vital importance. The following is one method of making a straight joint on a single lead-covered cable.

Typical Specification for Jointing.

1. *Preparing the Ends.*—Enough lead and insulation are trimmed off the two ends to leave each of the conductors bare for a length equal to a little more than half that of the copper sleeve or clamp. The lead, jute braiding or other protection is then trimmed back to leave from ¾ in. to 1 in. of insulation proper between the edge of the lead and the conductors. Some care is required in this operation ; an inexperienced man will use his knife held at right angles to the cable, and probably notch the conductors and cut the insulation close to the edge of the lead. In the former case, if the conductors are tinned, as with rubber or bitumen insulation, a chemical action may be set up between the exposed copper and the sulphur, tending to produce a fault, as has been observed in actual practice. The proper way to trim a cable is to cut partly through the lead, &c., holding the knife in a sloping direction, and then to break it off by bending it back.* The conductors when bared are cleaned with benzine.

2. *Tinning the Conductors.*—First protect the exposed insulation with tape, tied in place with thread ; fasten a single turn of copper wire round the conductor to keep the strands together. and then, holding the metal pot underneath, pour the metal over the ends with a ladle, using plenty of resin. The conductors should be sweated into a solid mass.

3. *Making the Joint.*—The two tinned ends are butted together with a split copper sleeve slipped over them, the open part of the sleeve being at the top, and the joint is then sweated solid, as in tinning the ends It is afterwards wiped smooth with a cloth and carefully examined underneath with a piece of mirror, all projecting points and roughnesses being removed with a file. For heavy cables the sleeve need not be split, but may have sweating holes or slots in it ; it should be about ⅛ in. thick and

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* To cut armouring, it should be partly filed through and then broken. A pipe cutting tool should not be employed, as it compresses the lead and insulation.

4 in. long for a cable of 0·2 sq. in. section and proportionately heavier for larger sections. An alternative and useful form of connection consists of two semi-cylindrical clamps, provided with four lugs at the corners, which are securely fastened together by strong screws. This is applicable to situations such as mines, where solder or blow lamps are undesirable.

The next process after the temporary tapes are removed is :—

4. *Insulating the Joint.*—The simplest method applies to cables laid solid, and consists in using no-tapes of any kind, merely filling in the trough round the joint with box compound of good quality. A number of joints, insulated in this way on heavy vulcanised bitumen cables laid solid in iron troughing by Callender's Cable and Construction Co., have been in use for many years without any failures. Probably iron troughing is the most suitable for this kind of joint, and it should preferably have-an iron cover. Its success depends entirely on the quality of the compound, and the manner in which the compound is filled in and allowed to set. If the joint is to be covered with a lead sleeve it is insulated with strong linen tape, kept immersed in boiling resin oil, the tape being taken from the oil only at the moment of using. The tape is tightly lapped on,* and made up to a thickness equal to $1\frac{1}{2}$ times that of the cable insulation. It should cover the exposed insulation and a $\frac{1}{2}$ in. of lead at each end ; the mirror should be frequently used during this operation. Mica is sometimes interleaved with the tape, but this is certainly unnecessary on low-tension joints, and for high-tension work probably reduces the dielectric strength of the joint, by causing air spaces to be formed between layers of insulation.

Any joint insulated with linen tape or other hygroscopic material must be sealed up water and air tight. This is done by covering the joint with a lead sleeve, previously slipped over one end, and plumbing it to the lead of each cable. The sleeve is now filled with melted jointing compound or thick oil, from one of two holes in the top ; the second hole permits the air to escape, and when the joint is filled they are both sealed up with lead caps. It is important that the compound be poured in, when perfectly fluid and very slowly. To ensure the proper filling of the joint during the process the sleeve should be gently heated with a blow lamp. Plumbing can only be learnt

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* To exclude air spaces.

by actual practice, but when limited to lead-covered cables it is not difficult to acquire the necessary skill, one of the chief precautions being to have the lead scraped clean and bright. Lead tubing is generally used, about $\frac{1}{8}$ in. thick, and in the case of low-tension cables with $\frac{5}{8}$ in. to $\frac{1}{2}$ in. clearance between its inner surface and the lead of the cables, and proportionately larger for higher pressures.

Plumbed lead joints are sometimes tested for porosity in the following way. Whilst the joint is still hot from the blow lamp, but before the compound is poured in, the filling holes are temporarily sealed with the lead caps and a little compound, and a mixture of soap solution and glycerine is smeared over the joint ; if any of the hot air inside is escaping, it will be indicated by bubbles forming over the leaky place. A good solution is formed of soap $1\frac{1}{2}$ oz., water 20 oz. and glycerine 15 oz.

Joints Insulated with Bitumen Lapping.

Joints may also be made on bitumen, rubber or lead-covered low-tension cables with lappings of bitite and wax, without any protecting box, but we consider that such joints should only be used on cables laid " solid," or where the joint is *suspended in air*, as in a drawn-in system , they should not be pulled into pipes, or at least only into dry iron pipes. Suitable bitumen lapping and compound being obtained, the joint is first painted with hot compound and the lapping then laid on spirally in short pieces ; very little tension can be employed, and it should be squeezed on to the joint with the hand rather than pulled on. After the first layer is applied, it is painted with wax and a second layer put on, every part of the lapping being painted on both sides. Three or four layers may be put on, and, if properly done with the right materials, the whole forms a homogeneous insulating and waterproof covering. If the cables are lead-covered the *lapping and wax* must project over the lead for about 2 in. at each end, care being taken to have the lead thoroughly clean. The whole insulation of the joint and the life of the cable depend on having a proper water seal between the lead and the lapping ; the kind of compound used is thus of the first importance. On no account should any attempt be made to use a fibrous tape in the insulating process. The whole joint is finished off and protected with a strong thoroughly impregnated tape wound on as tightly as possible when hot. All the

exposed conductors must be carefully tinned since the lapping is vulcanised.   This is a cheap and suitable method for service connections and straight joints on a drawn-in system.   When used on " solid " laid cables, the joint must be filled round with bitumen, and a special enlargement of the troughing must be made to contain it.   To make tee-joints by marrying, the strands of the branch conductor are divided into two bundles, and each is wound round the main cable in opposite directions, the whole being then sweated as before.   A tee-shaped sleeve may be used instead of marrying the wires in the case of heavy cables.   A jointer can make 12 or 15 such joints in a nine-hour day, if he has not to wait for ground to be opened up.   Thus, on a drawn-in system, a distributor can be very quickly renewed, although a large number of services are tapped from it.   On lead-covered cables these lapping joints break the continuity of the lead, and we believe this to be an advantage in most cases, but if the lead is desired continuous, a bond is readily sweated to the lead on each side of the joint.   In making this or any kind of joint the hands, tools and fittings should be kept scrupulously clean ; the hall-mark of a good jointer is cleanliness and neatness.

It should be clearly understood that not a single thread of braiding or other fibrous material must be included in the bitumen lapping (the insulation proper) of the joint.   The outside covering of tape is intended to serve merely as a mechanical protection, and to bind the lapping and wax tightly into a homogeneous whole whilst still hot.   It should not be lapped on to the lead beyond the bitite lapping as, being fibrous, when it is old and wet, it acts as a conductor and forms an electrolytic path across the joint, so that if the lead on one side of the joint should be not earthed and become " alive," and the lead on the other side is earthed, current will flow across the braiding and corrode the lead on one or other side of the joint.   The outer tape should thus be insulated from the lead by wax and bitite. When making straight joints with a sleeve it is important that the two ends to be jointed should be sawn truly square, so as to make as good a contact as possible where they meet. Similarly, when sweating connecting lugs or " ends " on to a cable, the cable ends should be cut square, so as to butt up against the end of the hole in the fitting, which should be drilled out to allow for this.   Attention to this detail may make over

20 per cent. difference in the conductivity of the joint, and with a cable carrying heavy currents this assumes importance. For example, a resistance of 0·001 ohm in a circuit carrying 1,000 amperes means a drop in pressure of 1 volt.

Vulcanised Joints.

In the days when rubber cables were largely used for underground work, vulcanised joints were generally made, and formed a capital job ; we have seen rubber cables drawn out, of which the only sound parts of the insulation remaining were the joints. Such a joint is made with specially prepared tapes lapped on spirally and temporarily protected, the whole being then immersed in a bath, which is maintained at a certain temperature with a blow lamp Sulphur was often used in the bath or mould, and also a low melting point metal alloy of tin, bismuth and lead. Full directions as to temperatures, time of immersion, &c., are supplied by the makers of these tapes.

Other joints are made with various special tapes, notably a tape used by the Admiralty, consisting of pure rubber backed with vulcanised rubber, but for buried joints compound or oil is principally relied on for insulation.

Aluminium Conductors.

Some difficulty is encountered in jointing aluminium conductors, because the wires are coated with a layer of non-
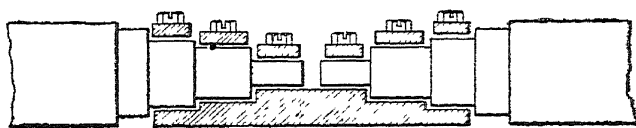
FIG. 133 —JOINT FOR ALUMINIUM CABLES.

conducting oxide, and it is not possible to sweat all the strands of a cable into a solid mass. Thus, in making a straight joint on aluminium conductors, the connecting sleeve ought to make contact with every individual strand of the two cables to be joined. This is done by stepping back the conductors on each cable, so that they are all exposed except the centre one (*see* Fig. 133). The aluminium connecting bar is shaped into steps, and fits under the cable, separate clamps or saddles being screwed down over each step. The whole joint must be filled round with compound to prevent corrosion.

For service joints the contact with the main cable need be only with the outer strands, but if the service cable consist of more than seven strands a stepped connection should be used. For small service connections, copper cables are likely to be always used, so that an ordinary clamp connection will serve to joint a copper service cable to an aluminium main in the method described below.

Protection of Joints.

Almost every joint (with the exception of those on a drawn-in system where they hang clear in the manhole chamber) must be protected by a suitable box, which is usually of cast iron ; but where the cable is lead-covered it is undoubtedly preferable to use a lead sleeve or box, for the obvious reason that, when properly applied, it protects the insulation by an envelope as impervious to water as the lead sheath pressed on in the factory. Manufacturers have long made it a standard practice to use lead sleeves for the straight joints on the factory lengths of cable laid by them, but the use of lead for tee and service boxes was not usual until comparatively recently. Possibly this was due to the fact that the jointer had to beat up a special box from sheet lead for every such tee-joint, and rather more skill in jointing, including a knowledge of plumbing, was required than in dealing with a cast-iron box. Within the last few years, however, cast-lead boxes made in iron chills have been used very extensively, thus avoiding the chief difficulties formerly met with. Boxes of cast lead, when produced in iron chills from *pure* metal, can be made of greater thickness than the ordinary sheets, and are quite non-porous and watertight. They have the further merits that the shape and clearances are fixed correctly once for all in the mould, even for boxes containing complicated fittings. The joint between the two halves of the box is made of a rebated shape, and needs only plenty of metal for soldering up to be perfectly watertight.

These two advantages materially reduce the skill required to make a satisfactory joint box, as compared with one beaten up of sheet lead. On the score of expense, a box of cast lead in place of iron has much in its favour, although it is often criticised as costly and involving extra time for jointing ; these views probably account for the slowness of its general adoption.

With regard to cost, a lead service box and fittings for triple-concentric cable can be bought for 10s. (simpler boxes costing less), and a good jointer, who has no road opening work to look after, will make four in a nine-hour day.

The one disadvantage of the lead box is its want of mechanical strength to withstand a blow from a pick or other implement, but this difficulty is easily overcome when the box is used with armoured cables, by covering it with a half-shell of cast iron, or with a few bricks or a tough board resting on an inch or two of sifted earth. On solid systems a rough protecting box of wood filled in with pitch or asphalte makes a very satisfactory protector. In filling the trench, care must be taken to bed the lead box on a layer of sifted earth free from sharp stones.
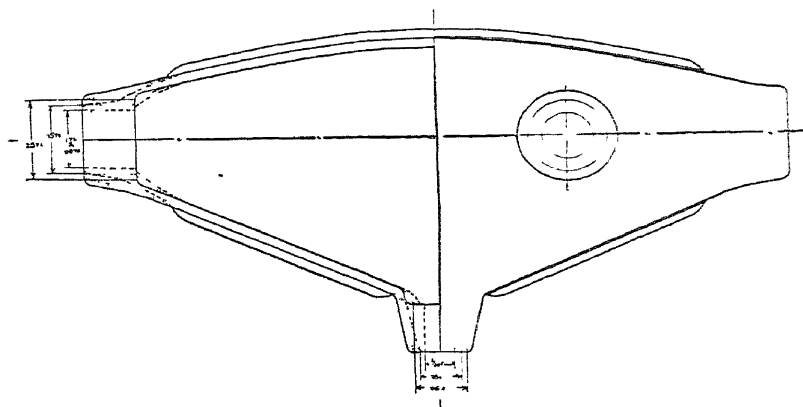
Fig 134.—Cast Lead Tee Box.

In making a lead box tee-joint, the fittings are first connected to the conductors and insulated, as will be described later for the different types. The two halves of the box are then fitted together, with the fittings in the middle, and the rebated joint where they meet is carefully plumbed all round with a solder stick and blow lamp ; afterwards the lead of each of the three cables is wiped on to the nozzles of the box (*see* Fig. 134). The box is finally filled with compound through holes in the top, which are sealed up by soldering lead plugs into rebated seats. For systems in which the continuity of the lead is systematically looked after, there is no method of jointing which will ensure this so well. The absence of faults, where lead boxes are in use,

is remarkable.   In one large town, where services are numerous and where faults were only too common, the whole of the cast-iron service boxes in certain streets were replaced by lead, prior to paving the roadway with wood blocks, so as to avoid the expense of tearing up the new and expensive road surface in the event of a fault occurring.   This change to lead boxes was thoroughly justified, and it has never been necessary to re-open the roadway due to faults at cable joints.

Cast-iron Boxes.

The cast-iron box has hitherto been the most popular, and it appears in a bewildering variety of shapes.   The properties it should possess are :—Mechanical strength, watertightness, clearance for the fittings and provision for filling with compound.   These properties are exhibited more or less perfectly in the designs in current use.   The original type for a straight joint on single armoured cables consists of two half-shells of approximately cylindrical shape meeting in a tongue and groove joint.   One or two partitions forming a gland at each end are bored to fit the lead and armouring, thus rendering the box compound tight.   Several filling plugs in the top enable the box to be filled with compound.

A modification of this design is a deeper box with a dished flat lid ; the cables enter through glands, which are split horizontally on the centre line of the cables, so that the top halves of the cast-iron partitions slide out and permit of the box being brought up to contain the joint, after all the fittings have been connected up (Fig. 135).   It is usual to bring the armouring through the first slide and a liberal length of the lead through the second slide, so as to enhance the watertightness.   In order to be able to use the same box for a number of different-sized cables, split wood bushes of the proper thickness are used to pack the cables in the holes in the slides, and thus make the glands of the box compound tight.   Plugs are inserted above each gland, and in the middle of the lids, for pouring in the compound, and it is sometimes the practice to use for the glands a special kind of compound, which is highly tenacious to metal, so as to ensure watertightness.

The bushes in these boxes, although made of hard wood boiled in oil, are often a source of trouble through electrolysis when they become waterlogged, as already explained.   It is better,

although not so convenient, to bore the glands, so that the lead and armouring are an accurate fit in them. The protecting boxes as described and illustrated in Fig. 135, when suitably proportioned, are adapted for use with single, multi core, concentric or triple-concentric joint fittings. By the employ-ment of the two half shells or split glands it is not necessary to cut the core conductor, a point of considerable value when service joints are numerous. Further, it is not necessary to bend the cables in fitting up the box. The successful use of this class of box depends chiefly upon the quality of the compound
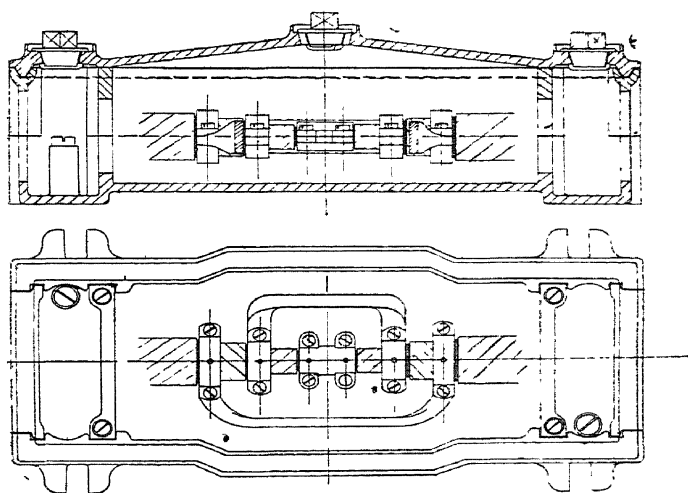
FIG. 135.—IRON BOX FOR PROTECTING JOINT.

employed, and the mode of filling, as the box is not completely watertight apart from the filling. The proper way to fill a joint box of any kind is worthy of attention. The compound must be thoroughly hot and fluid, and be poured in from one corner, so that it rises from below the fittings in a manner similar to molten metal rising in a mould. By taking this pre-caution the air is all driven out, and there are no air pockets left to impair the insulation. The box must be entirely filled, giving time for the compound to cool before the lid and plugs are finally screwed down. The dishing of the lid helps to

secure expulsion of the air and perfect filling.   The difficulty
of ensuring the absence of air pockets in compound filled boxes
of large capacity has recently been shown by the experimental
investigations of Mr. H. Dickinson to be much more serious than
was generally supposed.   As the compound cools it contracts
considerably, and this tends to produce a partial vacuum inside
the box, and to suck in air through the wood bushes of the
glands.   If the box is buried in wet soil or exposed to water it
frequently happens that the blowholes, produced by the air,
which leaks in and rises through the cooling compound, will
become filled with water and cause a short between the fittings.
As the blowholes are very often found close to the cable ends,
there is a grave danger of the water which is drawn into the
box soaking the paper insulation, and thus giving rise to faults
on the cables.

It has been found that the cooling and contraction of the
compound in a large buried box are not complete until after the
lapse of eight hours, and it is thus impracticable to keep the
road open for this purpose.   A method has, however, been pro-
posed by Mr. Dickinson which entirely prevents blowholes and
permits of the ground being filled in without delay.   This
consists in providing an auxiliary diving bell lid above the
ordinary bolted on lid.   A vertical tube, about 2 in. high and
perforated with a small hole at the top, is screwed into the
filling hole on the bolted lid.   A small diving bell cover is
screwed to the top of the tube, above the air hole, and this
permits of the access of sufficient air to compensate for the
contraction in the volume of the compound as it cools. Although
the box may be immersed in water, the diving bell, if suitably
proportioned, will prevent the water rising and entering the
box through the tube.   This trouble, due to contraction of
compound, does not apply to boxes with plumbed glands, or to
those of small capacity.   In comparing designs and prices of
cast iron boxes there are one or two points to be noted.   The
metal should have a minimum thickness of a $\frac{1}{4}$ in. for mechanical
strength ; the lugs also should be of ample section, so that they
do not snap when the bolts are tightened ; the surfaces at the
joint between the bottom and lid should be $\frac{3}{4}$ in. wide and care-
fully machined, or they may consist of a deep groove and a
substantial tongue.   The holding down bolts should be $\frac{1}{2}$ in. or
$\frac{5}{8}$ in. diameter, and in sufficient number to prevent any spring

at the joint. Brass or gunmetal nuts are preferable to iron, as they will not be found rusted to the bolts when the box has to be re-opened.

Joint and Service Box Fittings.

In jointing on single or multi-core cables, owing to the simplicity of the fittings (ordinary sleeves, tee-pieces or clamps),
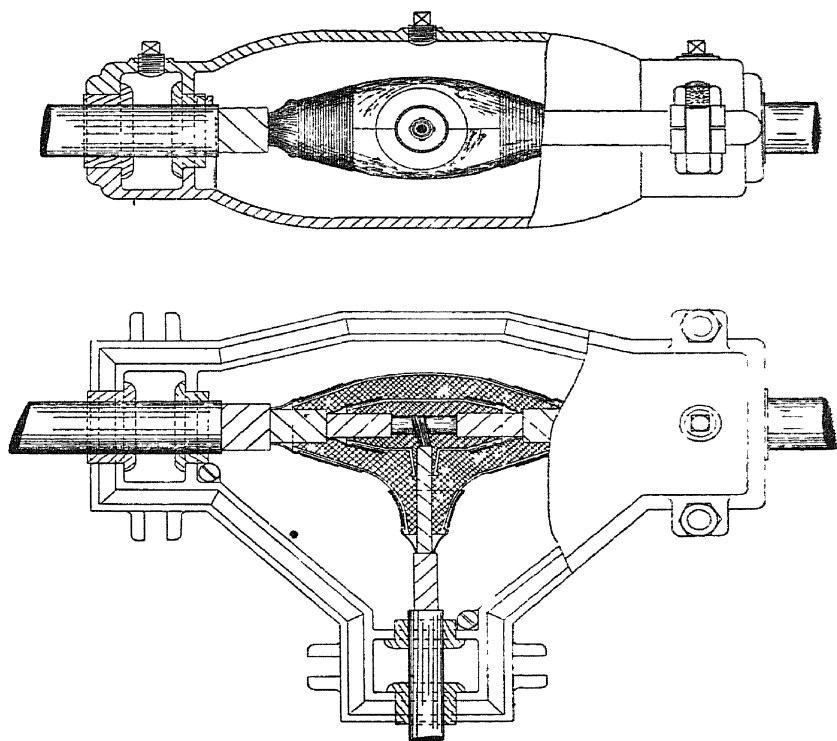
FIG. 136.—SHELL FITTINGS FOR CONCENTRIC JOINT.

there is not much possibility of materially varying the general designs of protecting boxes from those just mentioned.

On the other hand, a multitude of types of fittings have been evolved for concentric and triple-concentric cables, with a corresponding number of boxes.

C C 2

Concentric and Triple-Concentric Cable Fittings.

We propose now to give some notes on the merits and demerits of the various types of fittings, and of the boxes which have been adopted for their accommodation. The simplest form of these is known as the shell type (Fig. 136), which is used for the intermediate and outer conductors, the core being jointed or teed with close fitting sleeve connections just as

Elevation

Plan   End View
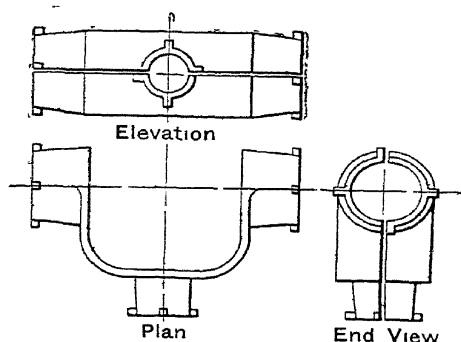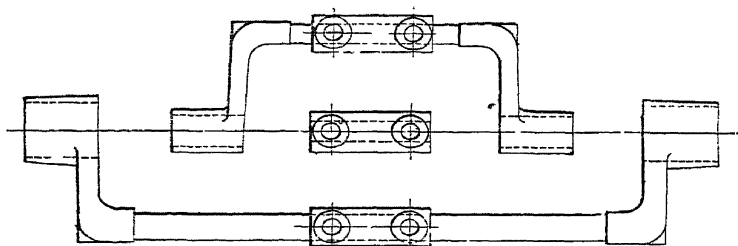
FIG. 137.

FIG. 138.

described for single cables. The shells are made of good quality tinned gunmetal in two cylindrical (tee-shaped for service joints) halves with projections or steady pins, which prevent them from sliding apart on the centre line. There is a clearance of about $\frac{1}{2}$ in. between the inside of the shell fitting and the sleeve on the core. At the ends the diameters are tapered down so as to be nearly the same as that of the layers of conductor they are to unite. The wires, trimmed to a length of

about 1 in., are laid down on the outer surfaces of the tapered ends, round which they are tightly bound with thin copper wire. A slight collar or a few projecting teeth prevent this binding wire from slipping off, and after it has been carefully sweated the whole joint is strong and rigid, and capable of withstanding a heavy pull on the cable due to heating and
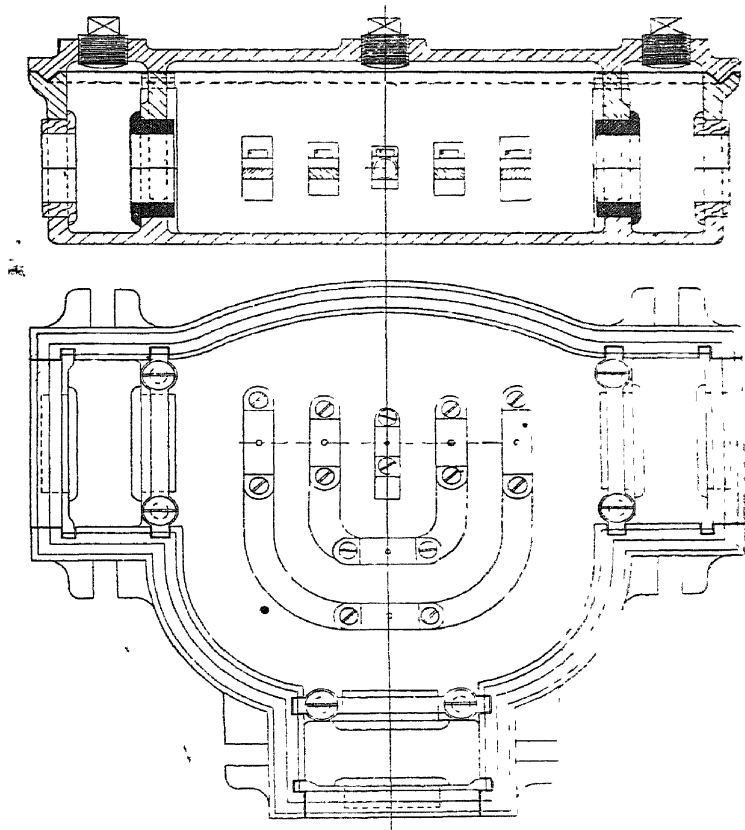
FIG. 139.—TRIPLE CONCENTRIC JOINT FITTINGS.

cooling or subsidence of the ground. The shell fitting appears in various modifications. For a tee-joint, the metal, except at the ends, may be cut away to such an extent that it forms an open cage of bars. Evolution has thus led to two varieties, shown in Figs. 137 and 138. In the first of these the conical

sweating ends and the bars connecting them are all split into two equal parts. In the second variety the bars are solid, but the ends are split and slipped under the concentric conductors before being whipped over with wire and sweated up. The shell type in any of its modifications possesses the advantage of excellent conductivity (equal to that of the cable) due to the perfect contact obtained on each wire and the efficient way in which the metal is used.

When complete shells are used a good mechanical protection is afforded to the insulation of the conductor immediately underneath it. The disadvantage is that it requires careful workmanship to prevent stray solder from getting under the fitting and damaging the insulation.

As regards price, it is the cheapest, on account of its compactness and simplicity and the smallness of the protecting box of lead or iron.

Compared with other types, the cast lead box containing shell fittings of any of the modified forms described above is, in the authors' opinion, the most satisfactory for concentric and triple concentric low-tension cables, on the grounds of conductivity, insulation, water-tightness, efficient bonding and cheapness.

Other Concentric Joint Fittings.

The most commonly used fitting on concentric cables, however, is the saddle clamp or plummer block type, illustrated in Fig. 139. The treatment of the core conductor is the same as before, while the outer conductor wires are trimmed so as to lie exactly in the semi-cylindrical bottom recesses of the outer fitting, which are bored to the proper size. The top half of each clamp is then screwed down tightly, and compresses the wires sufficiently to make a good contact To improve the contact and to protect the insulation on the core, which might otherwise be damaged by the pressure of the clamps, a stout cylindrical brass ferrule of the right length is pushed under the outer wires before clamping down. To make a successful joint with good contacts the screws must be strong and of ample length, and when sufficient pressure has been obtained between the wires and the ferrule there should be about $\frac{1}{16}$ in. clearance between the two halves of the clamp. It is ob-

viously difficult to get uniform pressure on each wire, but to facilitate this the hole in the clamp should be slightly oval instead of circular, when the two halves are fitted together. For triple concentric cables a second clamp fitting is used, as shown in the Fig. 139, a minimum clearance of $\frac{3}{4}$ in. being allowed in low-tension work between any of the fittings themselves and between the fittings and the cast-iron box. There is no taping required on the fittings with this joint, the compound giving the necessary insulation, and as it can be made quickly and examined easily at any stage it does not demand great skill

Elevation

End View
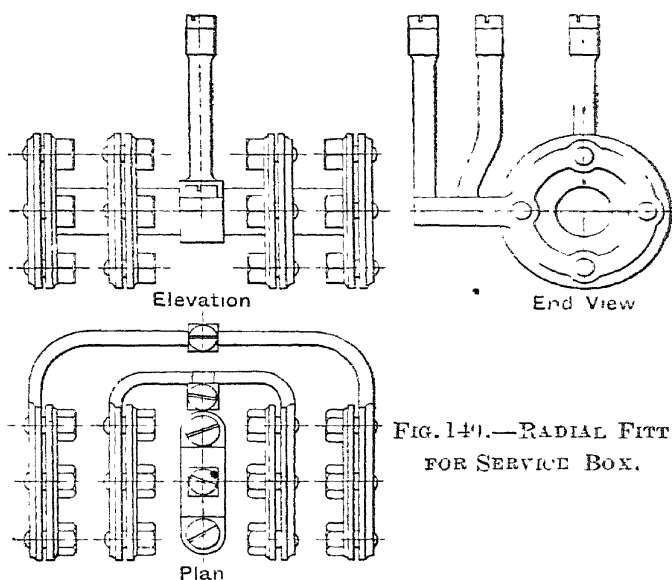
FIG. 140.—RADIAL FITTING FOR SERVICE BOX.

Plan

on the part of the jointer. These features, together with its moderate cost, probably account for its widespread use, but the possible dangers of poor contacts, crushing of the insulation and pulling out of conductors due to temperature stresses, should not be overlooked.

For concentric cables a better design of clamp fitting is that illustrated in Fig. 140. Here the fitting (known as the radial type) terminates in circular split flanges with clearance holes to permit of the passage-through them of the insulated inner conductor. The wires of the outer conductor, having been

carefully cut to template, are bent out at right angles to the axis of the cable, so as to form a rosette. The loose flanges are then tightened up by four set screws, and strongly compress the wires against the inside faces of the flanges attached to the connecting bars. The conductivity of this joint is certainly better than that of the saddle clamp type, particularly when the wires are circular. With flat wires in the outer and intermediate conductors care must be taken that they are not twisted, or only a few will make contact. For feeder cables of heavy section (above 0·4 sq. in.) made of stiff wires, some difficulty is experienced in forming the rosettes of wires, and to assist this they should first be bent and clamped on a stout steel template, which is a duplicate of the gunmetal fitting actually used. This joint may be protected in the type of box consisting of two half shells or that provided with split glands.

Bonding of Boxes.

An important feature in boxes on lead-sheathed systems is the bonding devices for connecting the lead of the cable to the cast iron, so as to give a path of low resistance through the box for stray or earth currents. passing along the lead sheath. In those types already considered the lead bond may be arranged in any one of the following ways. In Fig. 136 will be seen near each of the three entrance glands, a brass stud under which is clamped a stout piece of copper strip. Before closing the box these strips are carefully soldered to the lead sheaths and form a neat and cheap bond. An alternative method, adapted for the gland type of box, is to use lead bushes (Fig 139), each of which is bored to the exact diameter of the lead of the cable. These lead bushes are in two halves, the bottom one being put in position before the cable is laid in the box, and they are flanged to prevent them shifting horizontally. They are compressed against the lead of the cable by means of two $\frac{3}{8}$ in. screws, which connect the two halves of the split inner slides of the gland. This form of bond is highly efficient, and will permit of large currents passing along the lead sheath, via the box, without any arcing or damage to the lead. The only precaution in using it is to make sure that those parts of the box, which are in contact with the bushes, are clean and bright and free from compound. An additional merit of this system of bonding is the safety it affords against water working its way along the lead

sheath into the box. This is practically impossible on account of the close fit of the bonding bushes on the cable.

The method of bonding, which consists of making a plumber's wiped joint between the lead of the cable and a brass nozzle screwed into the box (Fig. 141), has the merit of providing a perfectly watertight gland for the cable, but it leads to an ex-
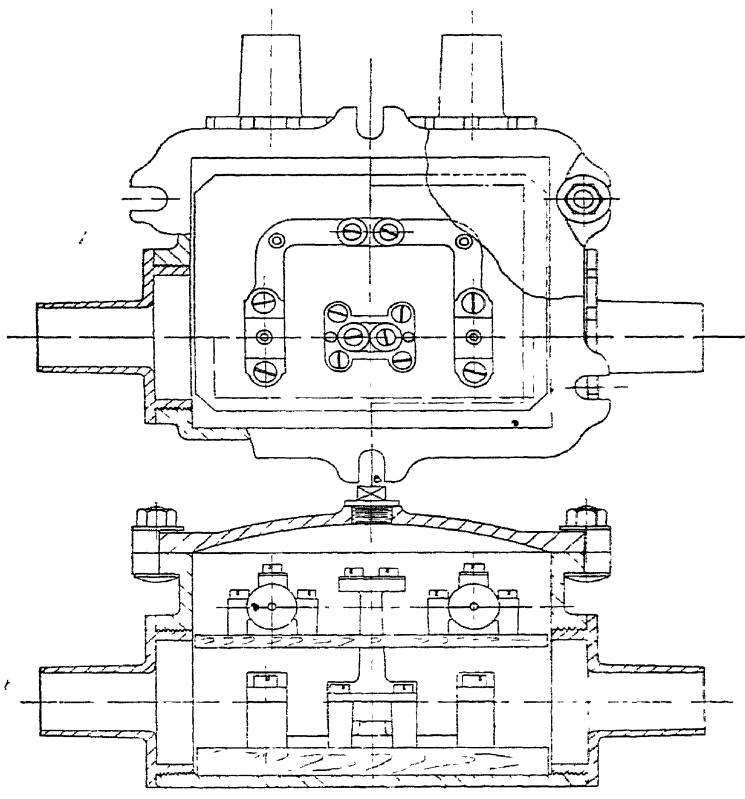
FIG. 141.—SERVICE JOINT BOX FOR CONCENTRIC CABLES.

pensive design. The price is approximately twice that of the sliding gland or split-shell type already referred to, the extra cost being due to the brass unions themselves and to the machining required. Greater care and length of time in jointing are necessitated with this type of box, and it has some further disadvantages. The core conductor of a concentric

cable must be cut at every joint, to enable the brass unions to be threaded on the cables, which after trimming must be bent for inserting in the box. Cutting the cable may be obviated by using split brass glands, the two halves of which are bolted together and then the complete glands screwed into the box. This means high-class workmanship and extra cost, if it is to be successful.

The cutting may entail trouble from increased resistance, or the withdrawal of the conductors from the fittings due to external stresses. Clamp-type fittings only are suitable for a box of this kind on account of the impossibility of placing the box round the joint after it is made, which is the chief advantage secured by other designs   Clamp fittings are often themselves sweated to ensure good conductivity, and it is possible to do this if the boxes are not too deep. To render possible the use of radial or shell fittings the box must be split at a machined joint on the centre line of the cables, which still further increases cost. In spite of their drawbacks the type is widely used where the importance of watertightness and efficient bonding are recognised without reference to cost, and especially where oil is used in the box in place of compound, as for switches in mining work and those used to isolate high-tension cables

In the authors' view, however, these desirable features can be secured at a fraction of the cost by the use of the cast-lead boxes already mentioned, excepting in the case of switches.

Another mode of lead bonding on concentric cables is to employ an additional G.M. clamp fitting, which unites the two ends of the cable lead, where they are trimmed inside the box. This requires a larger and more expensive box than that in which lead bushes are used, and does not appear to have corresponding advantages   The simplest bond of all is to bridge the box externally with a stout piece of bare copper cable from lead to lead. This class of bond being unprotected, is liable to electrolytic corrosion.

The desirability of bonding applies also to the armour, although not so strongly as to the lead. Armour grips to form a circuit through the box are generally used in Continental but not often in British practice outside mining work.   A projecting semi-circular lip is cast on the lower part of the box, and a strong cast-iron saddle clamp fitted with two $\frac{3}{4}$ in. bolts compresses the armour into the lower recess and makes

metallic contact with the box. The over-lapping of the steel tapes renders a good contact difficult to secure, and even when the tapes are carefully cleaned the conductivity is uncertain. In most cases, therefore, no attempt is made to bridge the armouring at a joint, but it is cut off as close to the box as possible, and prevented from springing open by a galvanised iron wire, whipped round the cut end. or prefer. bly it is brought through the first gland of the box

Specification for Joints on Live Concentric Cables.

No difficulty is experienced in the jointing of single cables when they are alive, as only one conductor need be exposed at each operation, but with live concentric cables the manipulation requires some care. and we therefore give below a short description of a safe method of making service joints under these conditions. When the distributor is fed from one end only, temporary bridgings of insulated wire must be used as the work proceeds, otherwise the operations are similar to those for a cable fed at both ends In what follows the service is assumed to be off the inner and outer conductors instead of the outer and intermediate, as this is the more complicated of the two alternatives. The first step after trimming away the lead is to bare the outer conductor to a template corresponding to the length of its shell or clamp fitting. It is now cut through in the middle, and the wires bent back over the lead, which is temporarily insulated with any common tape These outer wires are then carefully insulated, and the intermediate conductor exposed, when it is dealt with in a similar manner. being bent back over the outer. The core conductor is then bared, but not cut, and the inner of the service branch having been previously trimmed is connected to it, either by marrying. for small services, or by a tee-clamp for heavy cables. The permanent insulation of oiled linen tape is now applied to this joint in the core. The next step is to remove the temporary insulation from the intermediate conductor, trim the wires to the proper length, and either sweat them to a shell fitting or clamp them in the plummer block or radial device. There is no branch connection to this fitting, but if of the shell type it has a clearance hole for the insulated core of the service cable to pass through.

After this is insulated with tape the outer conductor can be dealt with, the outer wires of the service line being sweated or clamped to the tee-branch.

After insulating with tape, if required, the joint is ready to be laid in its protecting box.

Fused Service Joints on Concentric Cables.

When concentric cables were first introduced, it was thought necessary to provide fuses at every joint and service branch. This is by no means general now, but the use of fuses in buried service boxes still survives, although the fuse often consists of a piece of No. 14 copper wire. The general appearance of the standard design can be seen in Fig. 141. The box is usually called the double-storey type, as the main cable fittings are below the wooden tray to which the service fittings are attached. The cables enter through brass unions, and are connected to clamp fittings screwed to the teak board, which supports them on the bottom of the box. Short gunmetal stems rise from these through the upper board, and two or even three concentric or twin service cables can be coupled up through fuses to these stems. When a multiple service box of this kind is placed in line with a party wall a second service can be connected very cheaply by merely inserting the new cable through the second tapped hole, previously fitted with a blank gland, and adding another set of fuses from the main stems The top ends of the stems are kept just above the compound level to permit of this addition. Although the double-storied box is expensive the cost per service is not extravagant, when it is remembered that two or three can be taken off the same box.

It may be mentioned that single-storied boxes can also be modified to take two services, which are led through one large compound filled gland with two holes, or through two separate glands or brass unions. Unless the two services are completed when such a box is first fitted it is awkward to add one subsequently, as the box has to be cleared of compound and practically dismantled. The chief use of two, three and four-way service boxes is when rows of newly-built villas or cottages have all to be connected up at one time.

The double-storied box may be provided with the ordinary compound glands, instead of brass unions, and if it is split on the centre line of the cables this avoids the necessity for cutting

the core conductors, otherwise the arrangement of the fittings is similar in both forms. When mains, either armoured or solid, are laid under the pavements, as is customary, it is a great convenience to have an easy access to the service boxes so as to give facilities for testing and the location of faults. A neat castiron frame and cover on a small brick pit containing the box enables this to be done, and the extra cost is justified when dealing with busy streets where opening trenches is objectionable
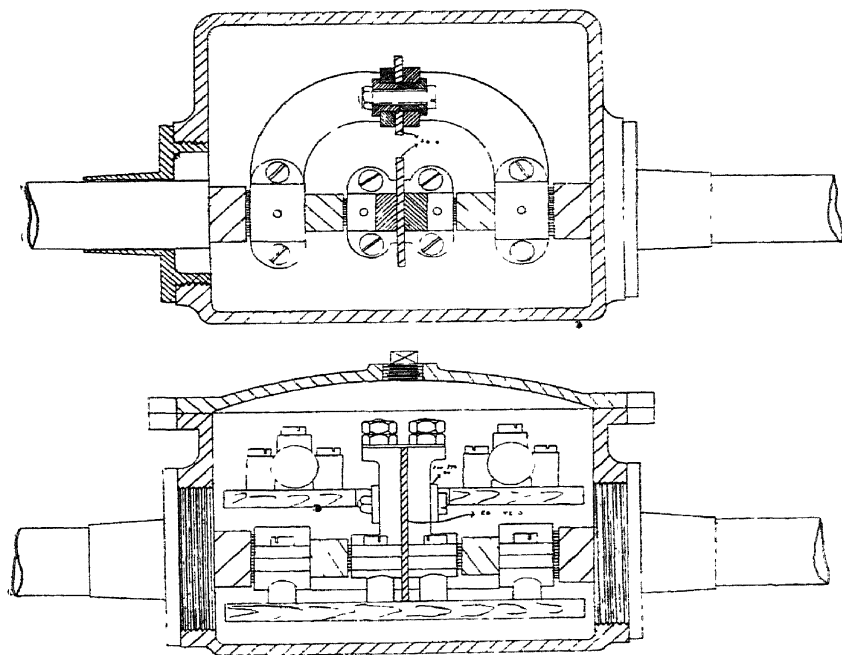
Fig. 142.—Disconnecting Box for Concentric Cables.

The double-storied box, placed in one of these pits, can be adapted for disconnecting the main cables as well as the services by the simple modification of dividing each rising stem into two parts separated by an ebonite strip and connected at the top by a stout copper link (*see* Fig. 142). A small number of these boxes judiciously distributed will prove of great assistance in mains testing and repairs. In a drawn-in system, a

brick pit, frame, and cover is always provided for each service, but the above method enables a solid system to approach it in accessibility.

Jointing on Multi-core Cables.

Boxes for this purpose are much simpler than those on concentric cables, and this is the chief inducement for paying the slightly higher prices charged for twin or three-core cables. The boxes are made in two half-shells of cast iron or lead, or the sliding gland type may be used (*see* Fig. 143). The chief point to be insisted on in the design is sufficient distance between the main glands to permit of splaying the three twisted conductors,
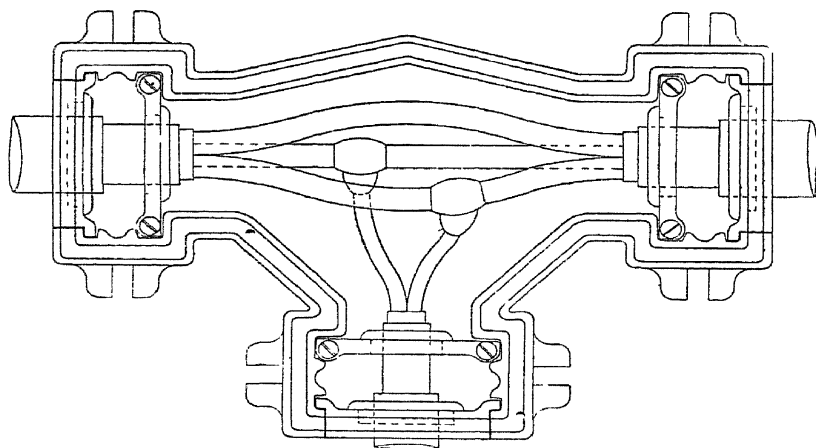
FIG. 143.—SERVICE JOINT ON 3-CORE CABLE.

so as to enable the service wires to be connected to them either by marrying or with fittings.

In some makes of multi-core cables the insulated conductors are wormed together with too short a lay, so that an average jointing distance of 11 in. or 12 in. is necessary for a tee-joint.

Only one conductor need be exposed at a time and it need not be cut, so that the jointer's work becomes very easy.

Separators of wood or other insulating material are often shown in illustrations of three-core boxes, but they are rarely used in low-tension work on account of the difficulty of opening

out the cores and keeping them in that position. In high-tension boxes porcelain separators can be used with advantage. The fittings of multi-core boxes are free from any complications ; they are merely three G.M. sleeves for a straight joint and simple clamps for a tee-joint, or the branch wires may be married to the main conductors.

Twin service cables are more convenient for their purpose than two singles on account of their cheapness and the simplicity of service and house fuse boxes. Concentric cables are still cheaper, but involve dearer boxes and labour in jointing. For long services, however, it may pay to use concentric cables even when the mains are multi-core. For four-core mains on three-phase systems with earthed neutral the same tee-boxes can be used as on three-core. In fact, when the ordinary two-wire service is taken off, the mode of jointing is identical, and even when all four wires are taken into the premises there is usually sufficient room in the box for the four clamps required.

Joints on Three-wire Mains Laid Singly.

When the armoured direct system is used with three single cables (practically now on the older networks only) a set of two or three small tee-boxes is employed for service joints, or a larger box may contain all three cable fittings. For the solid system with the three cables in one trough, a portion of this is cut away to permit of the insertion of a box which is provided with external lips to carry the ends of the cut troughs, and prevent a break in the compound filling, due to any displacement of the box and trough. The box itself may be of stoneware if the ducts are of this material, or, similarly, it may be of cast iron or wood. Sometimes the troughing is not cut, but a short piece of the cover only is removed and a shallow box and lid of cast iron fitted on in its place. The service cables pass through a bushed outlet in the side of this box.

The actual jointing in any of these cases is done by means of simple marrying, or by tee-clamps, and the compound filling is relied upon for insulation. If the filling is done carefully the added compound should unite thoroughly with that already in the trough and a satisfactory result is secured.

A compound of good quality is essential with this type of joint in any of its modifications. Cables of every kind may be laid on the solid system, and it is advisable when inserting a

joint box on any of them to provide troughing lips, so that the compound round the cable may be continuous after the joint is finished.

Cable End Boxes.

Since nearly every modern cable is insulated with hygroscopic material, precautions must be taken to seal this thoroughly against the entrance of moisture at exposed ends. For the dead end of a buried cable an ordinary straight joint box is used with the other cable-way suitably plugged. The conductors are trimmed and insulated and the box filled with compound.
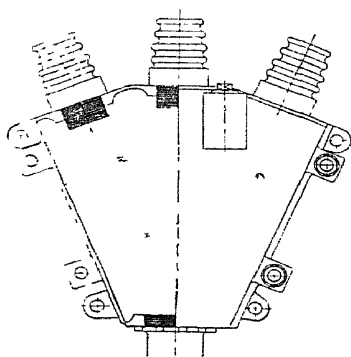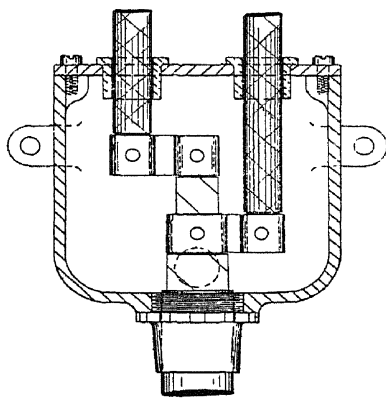
FIG. 144.   FIG. 145.

DIVIDING BOXES.

When the cable terminates in a sub-station or a feeder pillar, or under a switchboard, special types of sealing ends are employed, which serve also to divide a multi-core or concentric cable into separate rubber-insulated conductors or tails, for convenient attachment to the switches or fuses. Typical forms of these appliances are shown in Figs. 144 and 145. For high-tension cables the vessel containing the compound and fittings is of corrugated porcelain, or it may be of cast iron with long corrugated porcelain nozzles, through which the individual insulated conductors pass. Low-tension dividing boxes are either of cast iron (Fig. 145) or porcelain, but the clearances

are less and the outlets need only be bushed with wood. The cost of extra-high-tension end boxes for 11.000-20,000 volts is a considerable item in the total expenditure on short lengths of cable connected to switchboards. The British Insulated & Helsby Co. comment on a recent case, where the alternatives of using three core, 20,000 volt cables or three single cables with the necessary end boxes were estimated. It was found, owing to the simpler end boxes on single cables, that their employment meant a saving of 60 per cent. in the case considered.

High-tension Boxes.

The foregoing notes on cable boxes refer mainly to low-pressure systems.

In high-tension working the boxes are generally of the same types, but they are roomier, and give greater clearances between the fittings. For 2,000 to 3,000 volts the clearance of fittings under compound, without any other insulation. should be $1\frac{1}{2}$ in. Shell fittings for straight joints which are insulated with tape. should have a clearance of $\frac{3}{4}$ in. For higher pressures correspondingly larger clearances must be allowed. The filling employed should be a high grade of refined compound or oil.

In power transmission at extra high pressures too great care cannot be paid to the boxes. As far as possible straight joints only should be buried, and all branches should be dealt with in sub-stations. The great difficulty to be guarded against in industrial and mining districts is subsidence of the soil producing strain in the conductors and fittings. The transmission cables also tend to be run at high-current densities. and the consequent high temperature causes strain and distortion

An ingenious form of elastic joint to minimise these troubles has been devised by Mr. Vernier, of the Newcastle Power Co.. which is described and illustrated in '' The Electrician '' of March 10, 1911. The safe increase in temperature in three-core paper insulated cables, taking the initial temperature at 60°, is somewhere in the neighbourhood of 90°F., but the expansion of the copper conductors due to this temperature increase necessitates some means for allowing them to move freely without destroying the continuity of the cable at the joints. That this is so is clear when it is remembered that, in

a 200-yard length of cable and for a temperature rise of 90°F., the movement may be as much as $6\frac{1}{4}$ in., or over 4 ft. 6 in. in a mile.

Fig. 146 gives details of the usual type joint, in which AA are the two ends of the cable, B is the guide tube, and CC the flexibl braids, which are bound down to the middle of the guide tube, and also to the cable at EE. Each separate joint is contained in a micanite tube D. These expansion joints may be used with advantage on triple concentric cables which are especially liable to trouble from unequal expansion of the cores when loaded up. Some hundreds of these joints have been in use, many of them for 8 years, in the mining districts of Northumberland, Durham and South Wales, and have given every satisfaction to the power companies operating in those districts.
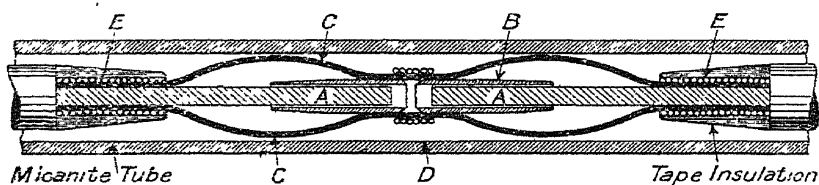
FIG. 146 —SECTION OF EXPANSION JOINT.

Joints being the most vulnerable parts of a high-tension cable, they may, in some cases, be enclosed in brick manholes, so as to be accessible, and in such circumstances a little slack cable may be left at each side of the joint to admit of a certain amount of tension, without unduly straining the joint. Extra high-tension cables for transmission purposes are usually three-core, carrying three-phase currents. Each core may be jointed with a cast gunmetal sleeve of a shape to fit the conductor. They are then insulated with linen tape (free from any dressings) taken fresh from boiling resin oil and bound on as tightly as possible over the joint and exposed paper insulation, to make a thickness of tape over the joint equal to $1\frac{1}{2}$ times the thickness of the paper insulation, the joint tapering at each end to the paper which is preferably stepped back.*

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* J. S. Highfield, " The Electrician," March 17, 1911, p. 92.

The three joints are then held apart by two porcelain discs, each containing three holes, previously threaded on to the cables. The whole joint is now enclosed in a lead box as previously described, and may be filled with compound or oil. The compound must be of high quality, and is preferably almost viscous at normal temperature ; it should be poured in very hot and very slowly, a blow lamp being used on the joint whilst the filling is being done. It should be allowed to stand 12 hours before being finally sealed, and if any shrinkage has taken place a final filling of compound must be given. The actual filling can hardly be done too slowly to avoid air-holes in the compound. The objection to an oil filling is that it may leak away down the cables, and this we have known to happen with jute cables, but its occurrence is not probable with paper cables, which contain plenty of oil between the layers of paper and between the strands of the conductor, and which are impregnated in vac o. In any case resin oil can be had of any desired consistency, and very thick oil used for covering the cable fittings in the bottom of switch boxes, into which three paper cables are led, has not been found to leak at all. The advantages of using oil is that it constantly impregnates the insulating tapes and prevents all air spaces round the joints, and, most important of all, helps to keep the joint cool. There is one point about making high-tension joints with tape soaked in oil which is worth noting. This is the temperature at which the tape is withdrawn from the oil. If the oil is very hot, it will all drain away from the tape whilst it is being wound on. It is better, after boiling the oil containing the tape, to allow it to cool appreciably before taking the tape out ; plenty of oil is thus incorporated with the joint. Comparative tests have proved the superiority of the joint made with the cool tape.

House Fuse Boxes.

The Board of Trade regulations specify the insertion of a safety device—a fuse, or its equivalent, on the service wires at the point where they enter a building. Fuses protected by cast-iron boxes sealed by the supply authority are usually employed for the purpose, and, for power installations especially they must be carefully designed. In many cases the fuses run at full load for many hours each day and yet

they must be capable of breaking the circuit with certainty as soon as a fault or short circuit develops in the consumer's premises.

It is impossible to illustrate or describe the multiplicity of types that have been evolved, but the following are the essential features characteristic of good designs —The terminals are mounted on a glazed porcelain trough or channel the two cheeks of which are sufficiently high to shroud the fuse and prevent arcing from the terminals to the box when the fuse blows.   To improve this protection against arcing the lid of the box should be lined with an insulator.

The terminal studs on which the sockets or thimbles are mounted should be at least $3\frac{1}{2}$ in. apart for 250 volt working and capacities up to 50 amperes.   For 100 amperes the distance should be increased to $4\frac{1}{2}$ in., and for capacities over this with 250 volts, and for all sizes with 500 volts the centres should be 6 in.   The terminal studs should be provided with heads deeply countersunk into the back of the porcelain, with the recesses carefully filled with a hard insulating compound.

For sizes over 50 amperes the cable sockets should not rest immediately on the porcelain base, but should be tightened against a nut or shoulder on the stud so as to avoid cracking the base.   Plenty of metal must be provided in the sockets with good surfaces for contact with the fuse ends.   Current densities should not exceed 250 amperes per sq. inch   The entrance nozzles should be bushed with porcelain, and $\frac{3}{4}$ in. clearance should be allowed between the copper thimbles and the box.   The details of the fuses themselves have been discussed in the previous chapter.

In small installations lightly fused, porcelain bridges or carriers for the fuses are now largely used.   They make contact on the terminals with spring clips, and are very convenient for quickly replacing a fuse without danger of shock.   They also, like the shrouding cheeks mentioned above, tend to minimise the arc when a fuse blows.   After this has occurred several times, however, a clip bridge, or an open base with the cheeks too close together, is practically useless owing to the metallic layer deposited by the arc on the glazed surfaces, and if a " short " has been violent the whole of the porcelain parts will probably be shattered.   Although main fuses of the " open "

type perform their functions satisfactorily when they are in series with the resistance of feeders, distributors and service lines, it is practically impossible for them to withstand a test directly across the 'bus bars, or on a heavy inductive load.

For power circuits, therefore, the best fuse to employ is the enclosed dust-type in a fibre tube, the contacts of which are either inserted into spring clips or screwed down on the terminal studs. In America this type is in general use for all installations.
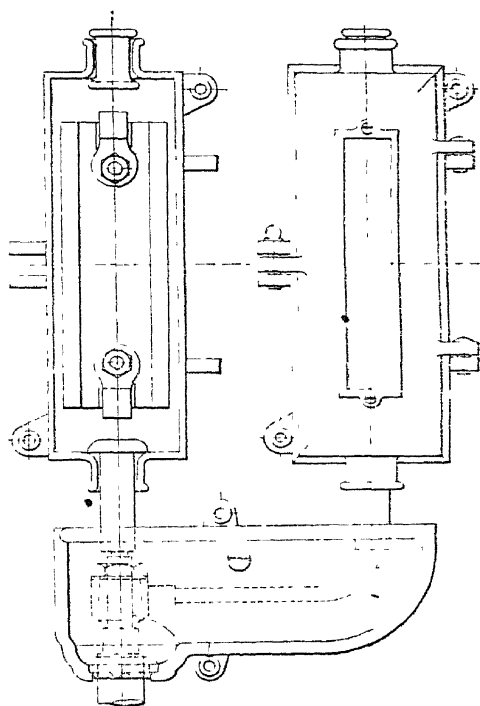
FIG. 147.—FUSE BOXES AND CAST IRON TROUGH FOR CONCENTRIC CABLES.

The cost of main fuses is now such a small item in mains expenditure that it is an unwise policy to use a box of 10-ampere instead of 50-ampere nominal capacity in order to save a few pence. With the increase in domestic applications of electricity it is awkward to find that the main fuses are too small when the consumer has been persuaded to add to his

load. For similar reasons it is well to be liberal in the use of three-pole fuses, as already mentioned. For three-wire installations the neutral box should contain two distinct fuses or links. In either two or three-wire installations each pole should be contained in a separate box, to avoid risk of a short between poles, and the sealing and dividing boxes for twin or concentric cables should also be distinct from the fuse boxes to avoid possible trouble through earthing. In alternating-current work, double-pole boxes are often used still, with the idea of minimising inductive drop, but this advantage is not worth the risk of a direct short or dead earth through the case.

In the illustration. Fig. 147, we give a typical design for concentric services, showing the channel porcelain bases, and the fittings for dividing the concentric cable in the sealing trough. The shape and size of the sealing trough is altered for the different types of cable employed, concentric or triple, twin or three-core, but in every case it should be split on the cable centre so that the trimming of the ends and the clearances between the fittings can be examined before the top half is screwed on and the whole trough filled with compound. Service cables may enter the sealing trough through a bushed hole in the side or bottom. In the latter case the cable must be carefully cleated to the wall so as to prevent the weight of an unsupported length from being carried by the fuse terminals.

The filling compound employed is usually harder than that employed for joint boxes, and is often a mixture of paraffin wax, or resin mixed with ordinary jointing compound.

Modern fuses boxes are all tending to conform to this general design with the necessary modifications to suit the capacity and voltage. At one time glass windows in the covers were largely used with the object of inspecting the fuses without breaking the seal of the fastening pin. The dust and dirt met with in the places where fuse boxes are usually fixed soon render inspection impossible without opening the lids, and thus the window is useless. As the glass is, besides, liable to be broken, it is very much better to have the lids entirely of iron. Although the H. O. Rules do not apply to the main fuses, which are the property of the undertaking, the tendency of modern design is towards the H. O. types, in which the fuses can be renewed without danger of shock.

Disconnecting Boxes.

The feature that distinguishes disconnecting from other kinds of boxes is accessibility. The usual buried joint in which the conductors and fittings are covered with compound is never meant to be disturbed. But for convenience and safety in working a sufficient number of disconnecting points must be provided on the network in order to subdivide it for fault localisation and to minimise the area affected by a breakdown. The condition of accessibility is best satisfied by overground pillars to contain the links or fuses, but they are more expensive, and are sometimes objected to as obstructive.

Pavement boxes of good design placed in a brick pit under a frame and cover are thus very largely used

The choice between fuses and links was formerly a knotty question, but the Board of Trade rule for delimiting feeder areas has now settled it satisfactorily. The modern method is to fuse the feeder, with a suitable allowance of overload, at the station, and to connect it direct to the 'bus bar in the feeder box or pillar * Each distributor is fed through a fuse having the same margin of overload as that of the feeder itself. At the points of minimum voltage between each feeder area a section box is provided containing light fuses just sufficient for the equalising currents These fused section boxes are mostly straight through ; but, for economy, the nearest 3 or 4-way box may be adapted for this purpose The practical and theoretical methods* for deciding on the position of these section boxes have already been dealt with at some length. As the network becomes loaded and further feeders are added the initial positions of the section boxes must be altered ; so that it is advisable to select a general design of disconnecting box, in which the links can if necessary be replaced by fuses

When a heavy fault occurs in a network properly fused the nearest distributor fuses will probably be blown first, thus cutting off the supply from their own feeder. The neighbouring feeders will now send current into the faulty district through the light section fuses, which promptly blow, and thus isolate

* It is, however, a debatable point still, if a feeder should be fused at all, on low tension three-wire systems. A fuse, with a carrying capacity of 700 or 800 amps., melting on a switch-board is very undesirable

the district. Measures can be taken immediately to run this district on a separate 'bus bar with a special machine, so as to maintain some sort of pressure until the fault can be localised down to a short length, which can then be disconnected prior to an accurate test with instruments.

For tracking a small fault which does not entail a partial shutting down, the subdivision of the network at the section boxes is essential.

In all boxes, except those at feeding and sectioning points, links only should be used. In practice it is poor economy to curtail the number of disconnecting boxes, and no solid box should be permitted where main cables branch.

Street Boxes in General.

The Board of Trade regulations require any street box exceeding one cubic yard in capacity to be ventilated, and it is advisable to ventilate all boxes to prevent any accumulation of gas and to minimise condensation. Leadless cables undoubtedly last better in well-ventilated ducts. The easiest method of ventilation is to provide holes in the box cover and a sketch of such a box is shown in Fig. 100. The lid is preferably hinged to prevent its blowing off in case of an explosion ; it is filled with a stone flag or with concrete, which should be grooved to prevent its becoming slippery. Such boxes are built of $4\frac{1}{2}$ in. brickwork, lined with cement plaster, and they should have a concrete bottom. Sometimes no bottom is put in, so that water may drain away, but the advisibility of doing this depends on the kind of soil ; if it be gravel or sand, it may serve its purpose, but in most clay or loamy soils, or on rock, such boxes would always be full of water in wet weather, and are also much more liable to accumulate gases than boxes built with concrete. It is sometimes impossible to keep very deep boxes free from water, and these may be drained through a trap to the sewer, or if the box is on the side of a hill, a pipe may be led down the hill, opening into the gutter. Boxes built in the roadway are of much heavier construction and the covers are generally filled with wood blocks set in with pitch, which require periodically renewing. They may be ventilated by leading a pipe to a grid ventilator built into the pavement. They should be built of 9 in. brickwork, but their use should be avoided as much as possible. Boxes

built in very wet situations are sometimes made with double walls and floor, melted pitch or bitumen mixed with pitch oil, being poured in between, and in this way they may be made quite watertight.* High-tension cables passing through the same box as low-tension cables must be painted a distinctive colour.

Disconnecting Boxes on Drawn-in Systems.

These are of the simplest construction, as all the fittings hang free on the cables themselves, where they cross the usual brick pit. In the three-way type illustrated in Fig 148 a gunmetal cone sweated on to each conductor fits into a conical seat in a metal block, and when drawn up by a nut makes excellent contact. Each block forming the bus bar for one pole may have any number of cables attached to it, and it is protected by a porcelain cap If these covers are removed only one at a time it is impossible for a workman to cause a short circuit. To disconnect any cable. the nut is partly unscrewed. and, before taking it right off, a sharp blow is given to the top of the cone to loosen it After unscrewing the nut the cable is firmly grasped below the cone and is readily pulled out. Very heavy currents can safely be broken in this way.

Incidentally it may be mentioned that the appearance of the arc when breaking an earth current is dissimilar to that of a load current. The former is generally reddish in colour and silent, the latter is blue and snappy, probably because the circuit is more inductive . these characteristic differences are useful to an experienced man when fault localising.

If a cable in a draw box is to be left disconnected a rubber sleeve is slipped over the end, and it can then be safely left.

The trimming of the insulation below the cone must be carefully done, following the procedure given at the beginning of this chapter.† Instead of having a cover of sticky tape, plenty of wax is used and a vulcanised rubber sleeve is slipped over and bound on with wire top and bottom. When properly done the only possible leakage is over the surface of the rubber, and this can only occur in damp boxes. Ventilation will prevent it

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* Brick boxes can also be made waterproof by coating them inside with a substance called " Ironite," supplied by the Ironite Co., Victoria Street, S.W.

† *See* pages 393—396.

entirely, but even where dampness is excessive the effect can be rendered negligible, with lead-covered cables, by trimming the braiding well back so as to leave 2 or 3 in. of bare lead below

Cables in Position.
(A)

Plan of Cone-block
(B)
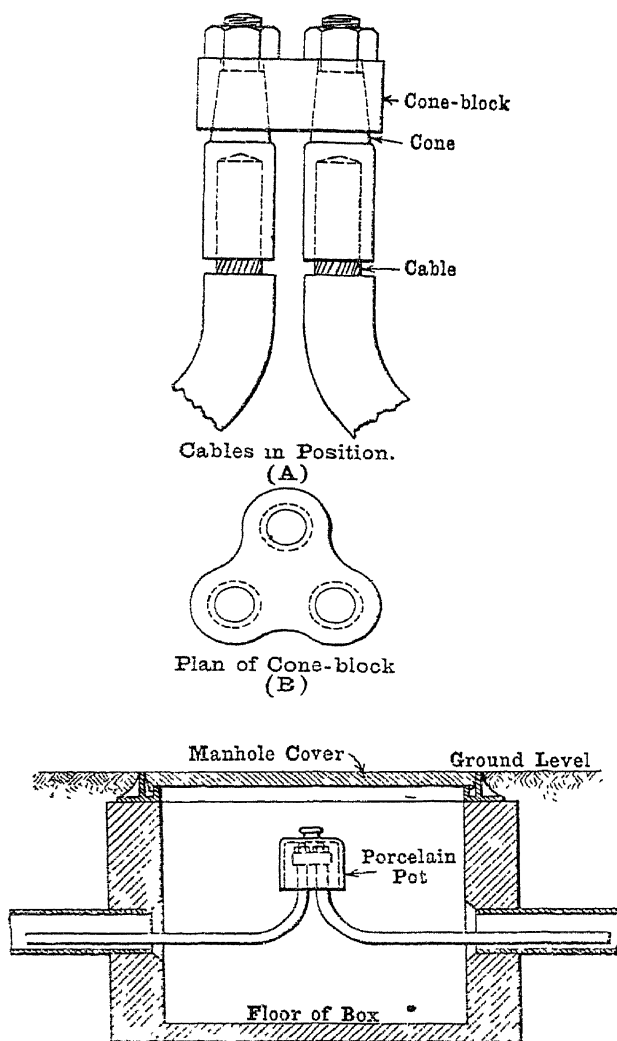
Fig. 148.

the sleeve.   If the braiding is left on, it forms a good medium for the osmotic transference of moisture, which tends to produce its usual corrosive effects.

Instances have been found where the lead was quite destroyed due to this cause, but the interposition of a surface of clean lead will stop the osmotic action. If leadless cables are used, a similar precaution may be adopted by twisting two pieces of wire round the carefully cleaned rubber or bitumen about 3 in. apart and connecting them with a piece of wire. As there is then no difference of potential between these two points, no current flows over the surface between them, and a gap is made in the path of the osmotic effect. It cannot be too strongly insisted upon that braiding on rubber or any other class of cable should always be treated as a partial conductor.

With heavy cables or those laid solid the arrangement of cone fittings and 'bus bars requires modification. In the former case it is difficult to bend the cable sufficiently, and in the latter there is danger in bending the cable on account of its being rigidly held in the troughing. In these circumstances rubber-covered bridging pieces are used, connecting the cable ends to the 'bus bars

When a drawn-in box is flooded with water the porcelain caps, unless specially weighted, tend to float off and sink. No great damage occurs, however, due to the short-circuit currents through the water, and the resultant earth current observed at the station is usually negative. The water rapidly boils away until its level is below that of the cones, of which only the positive is much damaged.

Cast-iron Disconnecting Boxes.

On systems of triple-concentric, three-core and frequently three-single cables the disconnecting links are accommodated in cast-iron boxes. The cables are led in, either through plumbed brass unions or compound glands with double slides and bushes, just as in the case of solid joint boxes. The earthing and bonding devices in the glands are also similar.

The dimensions of the box should be such that the dielectrics are well covered with compound, and below its level the minimum clearances formerly specified should be adhered to. Above the compound level, where the manipulation of the links is effected, as little metal as possible should be exposed and the clearances should be ample. The best designs are those that permit of each pole or phase being placed in a separate compartment shielded by slate fillets (Fig. 149).

Open links should be spaced with a break of 5 in. centres ; they should preferably be set in a vertical plane so that when the tightening studs are released a little the link can be lifted up, using one of the studs as a hinge while the other slips through the slot left for the purpose.   In testing operations the links are not removed, but when detached from one stem are tilted
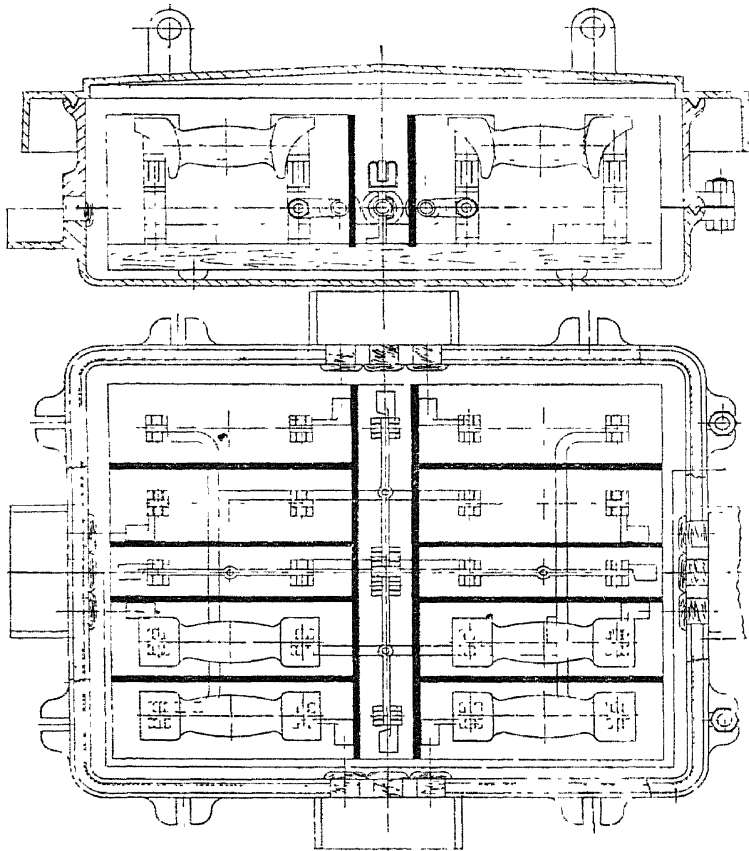
Fig. 149.

up and tightened by the stud at the opposite end into a clear position.   Insulated spanners should be used for releasing the nuts, and an insulated key fitting into a tapped hole for lifting the link, thus enabling it to be disconnected from the stem without danger of shock.

The method generally used for connecting the cables into the

box fittings is to sweat the conductor into sockets on vertical copper stems or pillars, which are supported either on the cables themselves or on a large base of impregnated teak or marble.
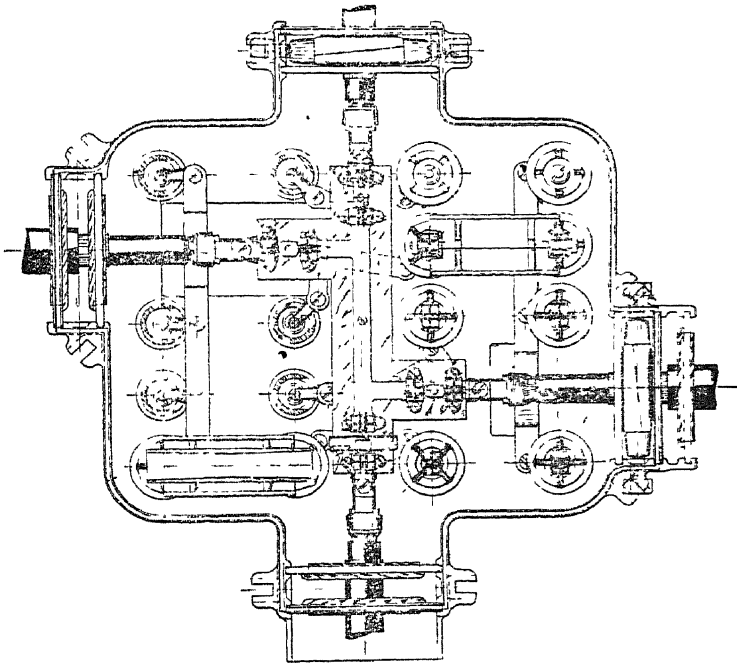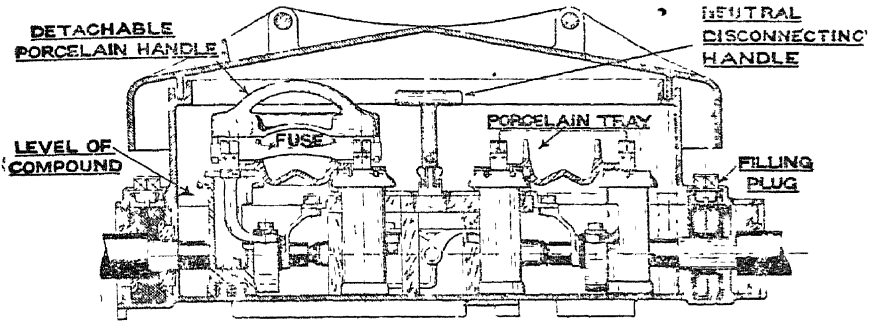
Fig. 150.

Unless the cables are large and stiff, and with a small overhang from the glands, the attachment of the stems to the cables alone is not to be recommended. Where no base is used the

'bus bars consist of heavy copper spiders, with a central hole. They are threaded over an insulated square pillar in the centre of the box and are thus prevented from being displaced. 'Bus bars of the spider type threaded on a central pillar are not generally satisfactory and their use is now practically discontinued. Where a base is used the stems are securely screwed down to it, each with a corresponding stem connected to the 'bus bar. Where teak is used it must be well boiled in oil, and, with either teak or marble, insulating feet should be provided and a number of holes bored in the base, these precautions being necessary to ensure the absence of air pockets when the box is filled with compound.

Box fittings are sometimes mounted direct on porcelain insulators instead of on teak or marble bases. Such boxes have a high insulation resistance to earth, and are safe to manipulate. A typical design is given in Fig. 150 (Messrs. Callender's Co.).

This question of strain in the fittings is more important than in buried joint boxes, as the removal of the links for test ng may afford an opportunity for enough displacement to prevent the r being again fitted over the studs. To guard against this effect the stems and all metal work for small cables should have sufficient rigidity, and therefore larger cross sections, than that required merely for conductivity. The strains due to change of temperature or subsidence of the soil may cause the conductors to be withdrawn from fittings of the plummer block type. It is preferable, therefore, to use radial fittings for concentric cable or to sweat the outer conductors to an end fitting of the shell type, which is in turn bolted to the vertical stem. It may be well to point out that troubles due to straining of box fittings are very irregular in their occurrence Some stations, even with large variations in the load on the cables, report no ill effects, while with others every possible safeguard must be used Those types of box in which each stem of the cable or 'bus bar is firmly fixed to a base plate of marble or bushed slate are the best for preserving the centring of the links against distortion.

Distributing Boxes on Multicore Cables.

For mains consisting of three singles or multicore cable the same general specification must be followed. With three and especially four core cables care must be taken that the position of the sweating thimbles on the stems does not necessitate long

pieces of cable straggling across the box (Fig. 151). On the other hand the splaying distance must be sufficient or the jointer will be set an impossible task in trying to get each conductor into its proper phase compartment if the cable happens to be cut so that the individual conductors do not correspond to the arrangement of stems in the box. The best plan is, by means of shaped links, to bring each of the four thimbles opposite to a cable opening and to give them a splaying distance of at least 4 in.
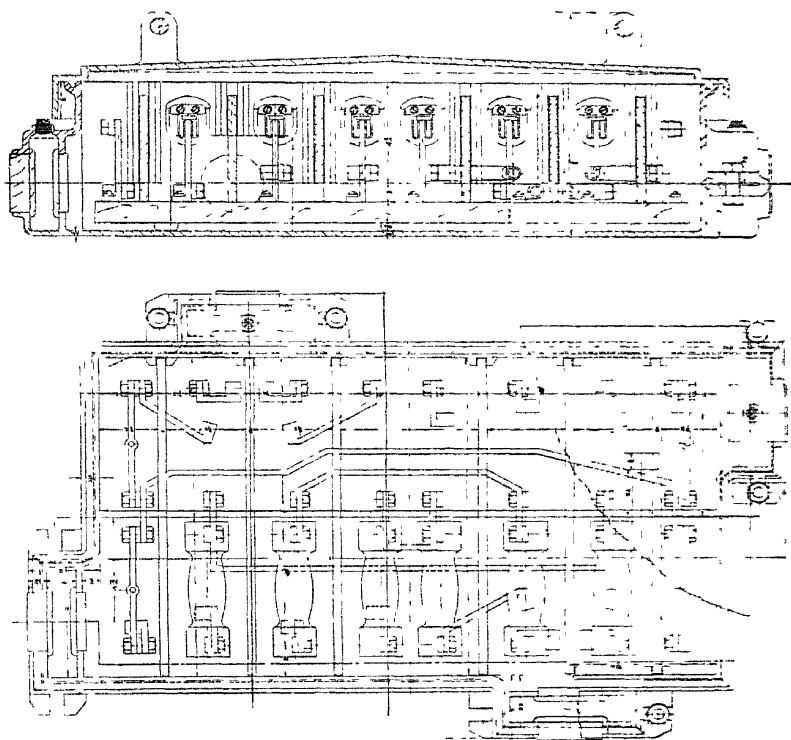
Fig. 151.

If the thimbles are all set symmetrically at 1 in. centres it is immaterial how the different phase colours lie naturally, as the amount of the necessary crossing of the conductors is but small. In all disconnecting boxes the current density at the contact surfaces of links or fuses should not exceed 250 amp. per sq. inch, where tightening bolts are used. In the case of spring clip contacts (which ought never to be used for currents over

100 amperes) the surface current density should not exceed 150 amps. per sq. inch   All fuses and links in the same box should be interchangeable.   Where fuses are held in porcelain carriers these must be so designed as to be easily removed even when the fuse has been overloaded for long periods.   Small tubular carriers shrouding heavy fuses are thus impossible, as they become too hot to touch, probably just when quick manipulation is a necessity

Castings for Distributing Boxes.

In any of the types of boxes mentioned, the right kind of lid raises many difficult questions.   By hypothesis it must give ready accessibility, but on the other hand the box is worse than useless if the lid is not reliably water-tight.   For situations where the box may be for weeks under water a faced joint with a good wide flange and plenty of swing bolts for tightening down is probably as good as any, if the jointer can be trusted to clean the joint and refasten it down carefully whenever it has to be opened.

A simpler type, and one that is easier to handle, is the diving-bell lid (*see* Fig 151).   The name explains the principle , in practice the over-hang of the flange on the lid which forms the diving-bell should be from 2 in. to 3 in , and 1 in. or more clearance should be allowed all round between the flange and the body of the box.   If the depth of the lip of the diving-bell is h, and the area of the annular space it encloses is A, the volume $h \times A$ should be 7 to 10 per cent. of that of the air inside the box together with that in the annular space.

In order to increase the water-tightness of lids of this kind it is usual to provide an auxiliary joint in a deep groove filled with resin oil.   This prevents condensation of moisture on the top of the compound, and also the creeping of water through the joint when the pit is flooded.   A diving-bell lid should be heavy, to avoid tilting by the hydrostatic pressure, but not too heavy, as the weight in conjunction with the suction of the oil seal may make it too difficult to lift.   If the weight exceeds 56 lbs., two lifting handles should be provided instead of one, as two men will be required.   The margin of safety against water entering under a diving-bell lid is usually high, as the head of water in the pit will not compress the air contained in the box more than 5 per cent. of its volume.

Owing to obscure causes—tilting, capillary effects, or condensation, water is sometimes found to penetrate into such boxes, and it is therefore advisable to inspect them periodically. The resin oil will also oxidise and requires occasional renewal.

High-tension Boxes.

The principles that govern the design of high-tension boxes are the same as for low-tension work, modified to suit the pressures employed. On extra high-tension mains it is a good rule to avoid tee-joints, disconnecting or otherwise, in the roadway, and to connect up all branches in sub-stations, wherever possible.

On high-tension mains similar precautions are advisable, but a well-designed disconnecting box should not be productive of trouble. Fuses are generally employed carried in porcelain tubes designed for high insulation, the cables being sweated into thimbles supported in porcelain insulators on a marble base. The live high-tension side should be contained in a com partment lined with glass or other insulator and quite distinct from the section containing the links on the earthed side

The lid should be lined, and where the fuses are in tubes baffle plates should be provided to prevent the molten metal from the fuse striking the iron box and setting up an arc to earth.

Diving-bell lids are the most suitable for this type of box. On high-tension mains it is always more or less objectionable to open an underground box in wet weather, and thus the fuses at points of branching are much better accommodated in pillars above ground.

Cable Boxes in Mines.

The designs of these boxes are similar to those described above, in regard to the materials of the boxes and fittings, the clearances, current densities, &c. The conditions under which they work and the Government regulations for the use of electricity in mines lead to some important modifications in the designs. Two standard types are illustrated in Figs. 152 and 153.
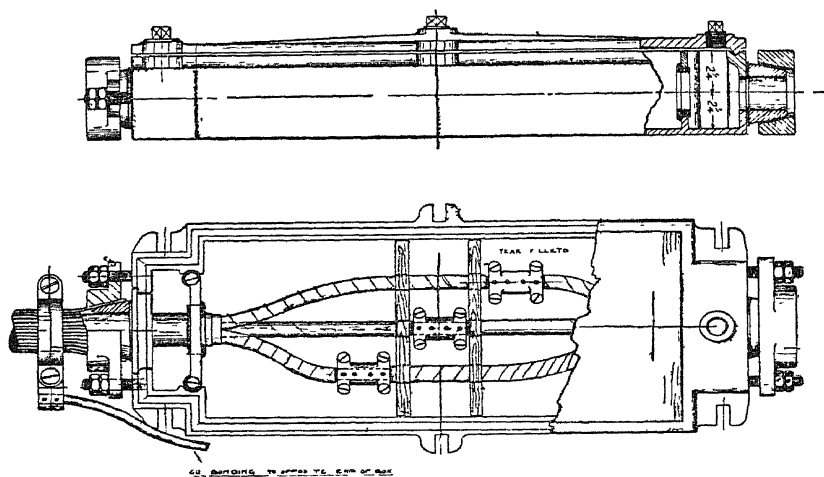
FIG. 152.—MINING STRAIGHT JOINT BOX.
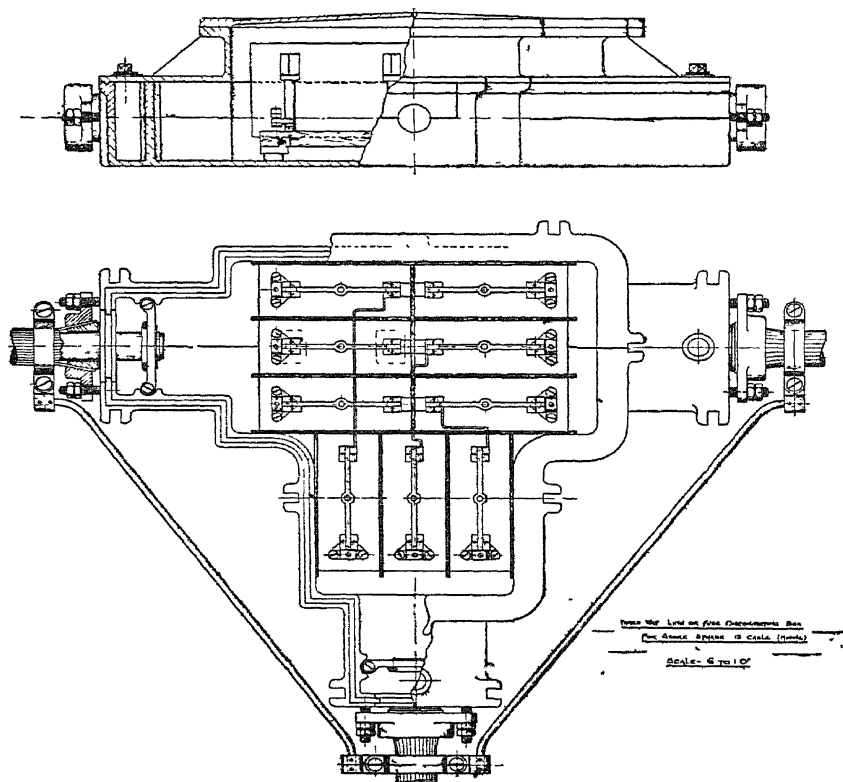
FIG. 153.—MINING THREE-WAY DISCONNECTING BOX.

The following are the principal points which should characterise mining boxes :—

1. The fittings should be of the clamp type, so that all connections inside the box can be made, even in a fiery mine, without the use of solder or blow-lamp.

2. Any joint between two parts of the box castings, if not under compound, should consist of machined faces, $1\frac{1}{2}$ in. wide, so as to be flame and gas-tight.

3. If lead-covered cable is used the lead should be mechanically bonded to the box at each inlet, either by means of a conical lead bush or by the semi-circular bushes already described. Plumbing on to a brass gland is not permissible.

4. The armouring wires, single or double, must be clamped to the box at each inlet. This is usually done by drawing them down, in one or two sets, over a conical bush, by means of a conical cap.

5. In addition to this an external bond of copper, equal in section to that of the smallest conductor, is clamped to the armour at each inlet, and thus ensures continuity of earthing apart from the bonds on the box itself.

Feeder and Section Pillars.

Mention has already been made of the superiority of pillars to underground boxes, and the principles which determine their position and the arrangement of their links and fuses have been indicated.

We propose now to give one or two of the salient features of good modern designs. The prospective user (in the first place) must not forget that the cost will be a good deal more than that of an underground box, and local authorities may endeavour to exact ruinous rentals where a company provides the supply.

The pillar must be well ventilated and have doors back and front to enable the whole of the fittings to be easily inspected (*see* Fig. 154). The doors should be fitted with locks of strong and simple design so that ready access can be had to the interior. Where pillars are bought separately from the gear it is preferable not to have lugs cast on for the support of the panels. Angle irons, which can be fixed in any position inside, are better mechanically and give greater flexibility in adjusting the clearances for the fittings attached to the panels. Polished marble is the best material to use for the panel on account of its high insu-

lation.   It is a good plan to mount it on insulating feet, and
to use micanite pads and bushings for the attachment of all
the copper fittings to the marble.   These precautions will
ensure that there is no leakage between poles or to earth.
Instead of a marble panel separate porcelain insulators are
sometimes employed for carrying the individual contacts,
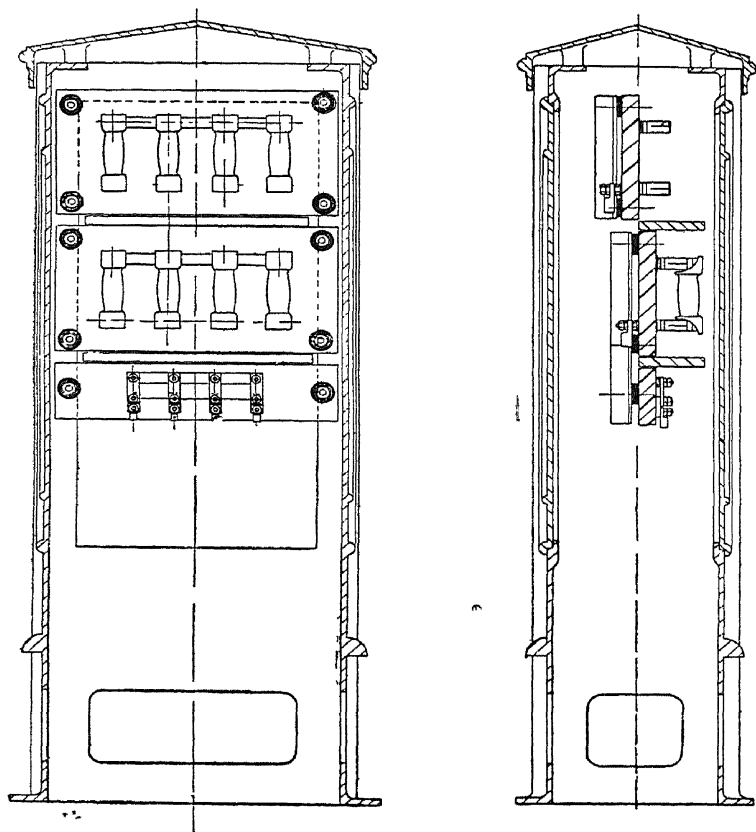
FIG. 154.

'bus bars, &c.   The insulators are fixed to a metal frame, which
is itself insulated from earth by porcelain feet.   For a pillar at
a feeding point the feeder cables should be connected direct to
heavy copper 'bus bars without the intervention of fuses.
Quick-break switches are sometimes advantageous on the
feeder cables.   The fuses are mounted in substantial holders

of porcelain, or teak lined with mica. Teak handles do not tend to get chipped or broken like those made of porcelain, a point of some importance where the fuses are often disconnected, and they entail no real danger of being set on fire.

The same principle of providing ample contact surfaces in the tongues and clips carrying current applies to pillar fittings just as to those in disconnecting boxes.

It is advisable to have the terminals designed for ammeter leads to enable the current in each distributor to be read off when a fuse handle is withdrawn. Enclosed fuses carrying the whole current or the composite fuse of tin and copper already mentioned are the safest in use.

When open fuses are employed, it would seem preferable to arrange them horizontally as there is then not so much tendency to the production of a flaring arc, but such an arrangement leads to complication in the cable connections at the back of the panel.

With the usual method of having the fuses vertical and those for each pole or phase mounted on a separate panel, destructive arcing from the fuses can be prevented by having a wide marble fillet inserted between each panel of different polarity, although there is still the possibility of all the fuses of one polarity melting due to the " sympathy " effect.

Where the mains consist of single cables the ends are trimmed and insulated as described for manhole boxes. For three-core and triple-concentric cables special dividing and sealing-off ends must be employed. There are various methods of doing this ; one is to have a sealing trough of porcelain, or iron with porcelain nozzles, in which the cable is subdivided into three or four single tails of rubber-insulated conductors, which are led to their corresponding panels. These troughs are mounted in the base of the pillar above the level of the pavement.

In order to avoid the use of rubber insulated tails the British Insulated and Helsby Co. have introduced an ingenious method of sub-dividing each cable in an insulating tube, which has the fuse contacts mounted directly upon it (*see* Fig. 155). These tubular units are fixed on a panel, and they render a second door at the back unnecessary. The insulating tube in which the cable is divided is filled with compound and forms a very compact arrangement but somewhat difficult to fit properly.

As a result of the fatality at Eastbourne due to a taxi-cab colliding with a H.-T. pillar the Board of Trade has recommended that special precautions be taken in the case of H.-T. pillars where there is any possibility of similar collisions occurring. Some of the recommendations are very costly and rather impracticable. The point to be aimed at is either to make the pillar so strong as to withstand any external blow, or else to line it with a flexible metallic earthed shield, which would be certain to earth any of the displaced H.-T. fittings after an accident, and thereby obviate any danger of a fatal shock.

Some engineers are installing pillars with the internal earthed lining, but from our experience we find that complete safety is secured in a cheaper way by building up the pillar carcase of No. 14 sheet steel on a strong angle iron frame. This will withstand any ordinary traffic collision, and even if the pillar were so much distorted that the fittings touched the case, this being earthed would effectively protect any passer-by who happened to touch it.

The appearance of the pillar does not suffer by substituting steel for the usual cast-iron construction.

Transformer Sub-Stations.

Static transformers with their switchgear should, wherever possible, be placed in chambers above ground. For extra-high-tension circuits nothing else is permissible.

On power systems sufficient accommodation can usually be obtained free of charge in a suitable part of the consumer's premises, the transformers and switches being partitioned off by brick walls or screens of expanded metal. The doors must be provided with special locks so that only the supply undertaking's employés can obtain admission. The consumer will usually have no objection to allow the sub-station to serve other circuits besides his own.

Where the sub-station has to furnish the supply at low tension to consumers of moderate size, and none of them is large enough to necessitate a special sub-station, an endeavour should be made to rent a small piece of land for the erection of the transformer house serving the group. In many cases, however, such land is not available or is too costly, and resort must then be had to chambers constructed under the pavement.

The materials used may be either concrete or brick, and great care must be taken to ensure watertightness. The difficulty in effecting this is due to the water in the soil being occasionally under considerable pressure. Water can be kept out by building a double wall with a space between and filling this with bitumen poured in very hot and fluid as the work progresses.

The roof is formed of concrete and iron girders or of ferro-concrete with a bitumen covering. The chamber should have a false floor consisting of a wooden grating, mounted on porcelain insulators, thus minimising the danger of shocks to earth. Access to the chamber is obtained through a manhole leading to an iron ladder or a set of foot irons. The manhole has a double cover ; the outer of iron filled with concrete, is hinged at one side, while the inner (also hinged) consists of an iron grid capable of carrying passenger traffic. The outer cover is kept open and the grid shut down when work is in progress in the chamber.

Good ventilation is essential, otherwise in temperate climates bad insulation will be caused through condensation of moisture. For ventilation purposes a pipe may be led from the floor level to a grid, preferably built into a neighbouring garden wall to prevent flooding. Circulation of air is ensured by leading another pipe from the roof of the chamber to a similar grid.

Any water actually present in the chamber should be drained into a sewer through a non-return trap. The manhole cover should also be drained ; a pipe from the groove passing down the inside of the chamber, and led into the drain, is convenient and helps to keep the trap full.

An important point in the construction is to see that the manhole is large enough to pass the gear in and out. It is undesirable to bring lead-covered cables in near the roof and drop them down to the switchgear, as the oil runs down and the end is difficult to seal.

This difficulty is got over by using bifurcating or trifurcating boxes close to the point of entry. The cables are sealed into these, and rubber-insulated conductors, or preferably fire-proof cables passing through long corrugated porcelain bushes, are led from them into the switches. The dividing trough and fittings shown in Fig. 156 is one of the best devices for terminating the cables in sub-stations.

Transformer chambers are sometimes made of flanged cast-iron plates with machined joints bolted together so as to form a kind of underground tank. Where many chambers are required of a standard size this construction is good ; it is quite watertight, but expensive in odd sizes.

In residential districts, or generally where the load is small, the types mentioned are rather costly. For such conditions a
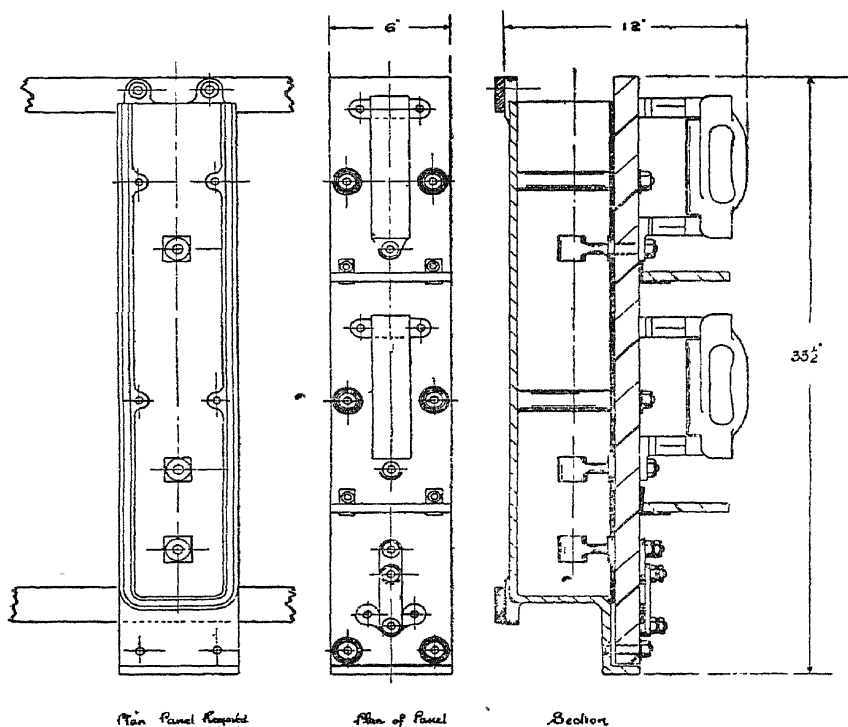
FIG. 156.

single transformer placed in a watertight cast-iron tank under the pavement is well adapted. This should have an inner cover as well as the outer cover flush with the pavement. The cables are preferably introduced through brass glands screwed into the case, and if lead covered, a plumbed joint is made between the lead and the gland ; this makes the point of entry watertight and also efficiently earths the case. A saucer containing calcium chloride should be kept in the case

to take up any moisture from the air, which is continually changed by a kind of "breathing action"* taking place. If the case is filled with oil, a stand-pipe or other provision should be provided for expansion. Formerly the switches and fuses were mounted above the transformer and access was obtained to them through the frame and cover. It is much safer and more convenient in working, however, to house the switchgear in a pillar close to the tank. When the transformer is small a composite pillar is sufficient to contain both the high-tension and low-tension gear in separate compartments, but it is generally preferable to have a different pillar for each pressure. A suitable design of high-tension pillar is illustrated in Fig. 157.

The high-tension feeder from which the transformer is supplied can be disconnected in the pillar, and thus the transformer ·can at any time be safely inspected or handled. Sometimes a large pillar or kiosk is used, which has sufficient space to contain above ground not only the transformer, but also the low-tension and high-tension gear. The transformer is carried on steel joists just above the pavement level, and in the upper part of the pillar access is afforded to the high-tension fuses by a door on one side, with a corresponding arrangement on the opposite side for the low-tension gear. In England this kind ·of sub-station is not common, as a large kiosk in the street is not tolerated so easily as on the Continent.

Its utility is best demonstrated when opening out new districts with an uncertain amount and incidence of load, as a kiosk with its contents can be easily shifted to a new position if required. Where underground boxes instead of pillars are a necessity, ·special care must be taken with the design of the switches, one of which is shown in Fig. 158, designed by Mr. F. E. Hammond ·of Edinburgh. This is an extremely handy and safe arrangement ; the fuse, which is contained in a glass tube, cannot be touched until the plug switch is withdrawn, and when this is done all exposed parts above the top ebonite plate are " dead." The bottom of the cast-iron containing box is filled with very thick resin oil to above the level of the entering cables, and .above this is poured thin refined resin oil, to just below the level of the ebonite plate ; the switch break is thus made under ·oil. The same switch may be used to control branch mains, and

* K. C. Randall, " Proc." Am I.E.E., Vol. XXVIII., pp. 247-65.

with a slight alteration it may be inserted, without the fuse, in long high-tension mains for testing purposes, and it then has the advantage that one may safely test the main one way by going to one box only ; in other types one must go to two boxes, so as to make the box one desires to test from completely " dead."
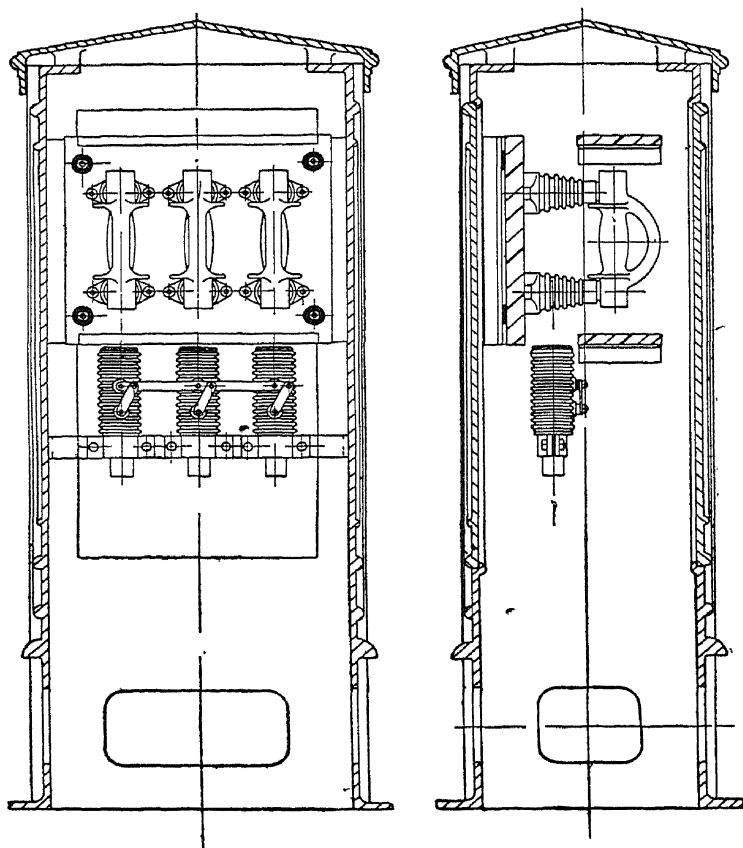
FIG. 157.

The commonly urged objection to this or similar types of box is that the cables must be severely bent in order to insert them, as shown in the first sketch in Fig. 159. The second and third sketches show how the cables may be inserted without undue bending.

The object of the two oils being used is to prevent the thin oil escaping along the cables. The bottom oil may be made quite solid if desired, by dissolving sufficient resin in it when boiling. It might be thought that the thin oil on the top would gradually dissolve a share of the resin out of the bottom layer and the whole come in time to an equal consistency, but this is not the case provided the oil is not unduly heated. Various jointing compounds have been tried in place of the thick resin
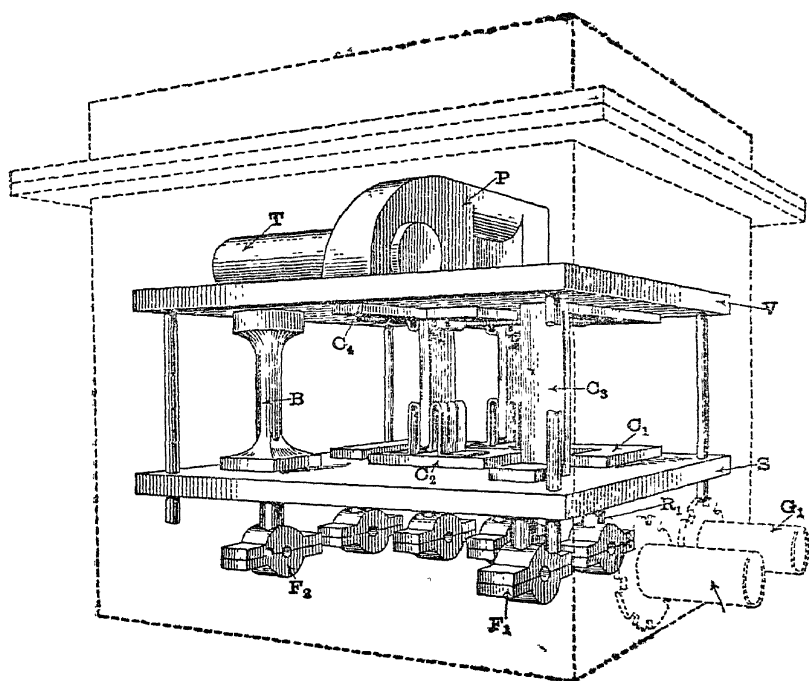
FIG. 158.

oil, but both resin oil and mineral oils are found partially to dissolve them, with a consequent fall in insulation resistance ; sundry high-resistance faults have been traced to this effect. Mineral oil also partially attacks the thick resin oil, and for this type of box the combination of resin dissolved in resin oil, and refined resin oil is undoubtedly the best.

Referring again to Fig. 158, P is the switch handle, which locks the fuse cover T ; V is the ebonite top piece and S a ,

slate or marble bottom piece. F_1 and F_2 are clamps for the branch cable which is to be controlled. The current from the inner fitting F_2 passes by way of B through the fuse contained
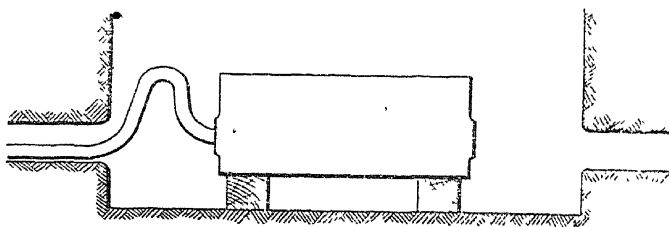
(1) INCORRECT METHOD OF INSERTING CABLE.
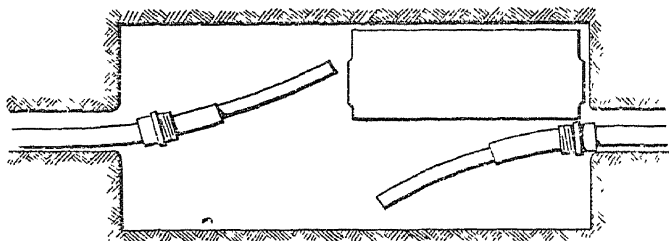
(2) CORRECT METHOD, CABLES TRIMMED, GLANDS SLIPPED ON TO CABLES AND CABLES SLIGHTLY BENT.
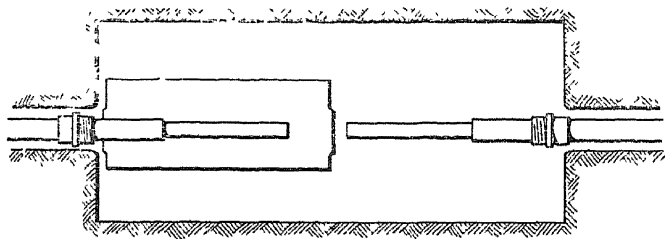
(3) BOX SLIPPED ON TO ONE CABLE AND SECOND CABLE STRAIGHTENED READY FOR BOX TO BE SLIPPED BACK ON TO IT.

FIG. 159.

in T, to C_4; thence through the switch blade to C_2, and so on to the inner clamps of the main cables. The outer circuit is from F_1, through C_3, through the switch blade to C_1 and so to the outer clamps of the main cable.

CHAPTER XIII.

COSTS OF CABLES AND CABLE WORK.

Cost of Cables.

The cost of cables varies with the price of copper, and when they are lead covered, also with the price of lead.

The price of 600-volt paper-insulated single-core lead-covered cables follows a law represented by the formula :—

$$\text{Cost per 1,000 yds.} = 5\text{·}38 \ . \ \text{P} \ . \ x + 15 + 228\text{P},$$

where $\qquad$ P = cross-section in square inches,

$\qquad x$ = cost of copper wire in £ per ton.
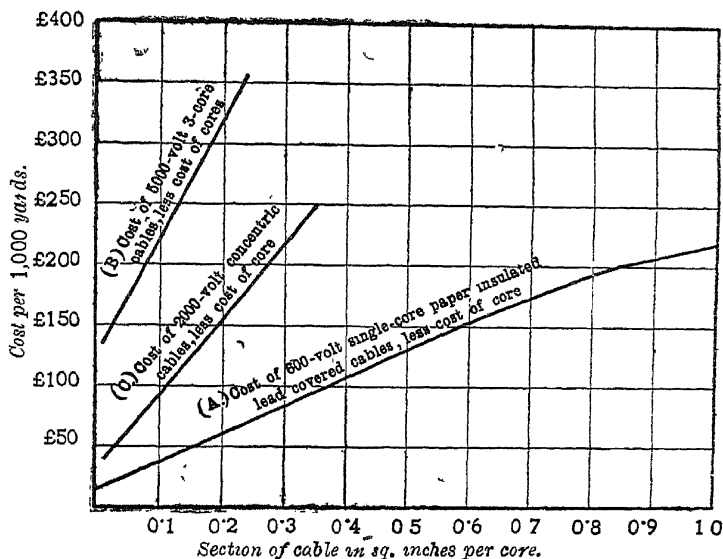
FIG. 160.

$5\text{·}38 \ . \ \text{P} \ . \ x$, represents the price of the copper core, with 3 per cent. allowed for stranding, and $(15 + 228\text{P})$ represents the cost of the insulation, lead, labour, &c.

The cost of the actual material used in insulating and lead covering follows a law represented by the formula :—

$$\text{Cost of material} = \text{A} + \text{B}\sqrt{\text{P}}.$$

Since the cost varies with the diameter of the core, or cost varies as $t^2 + 2td$, where " t " is the thickness of insulation and lead, which is constant for any given voltage. Owing, however, to the influence of works charges, labour and profit, the actual cost of a set of cables, minus the cost of the core, gives a nearly straight line law, the equation to which, worked out from English manufacturers' quotations is $15 + 228P$; £15 represents the cost of insulating and lead covering a single infinitely small strand of wire, if the price of lead is about £12. 10s. per ton. This formula gives costs a little high for cables above 0·8 sq. in. section, and a nearer figure will be obtained by using the curve in Fig. 160.
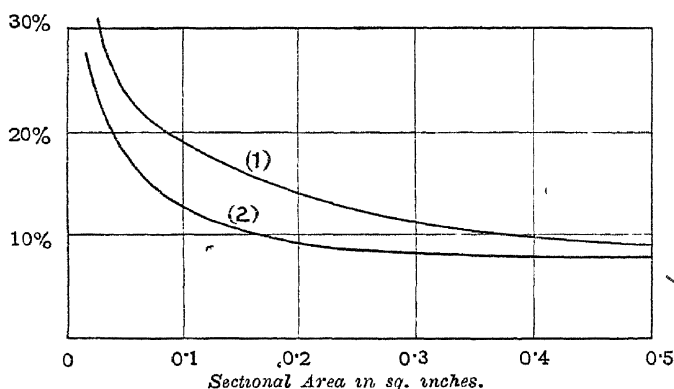
FIG. 161.—SHOWING PER CENT. INCREASE IN COST FOR (1) ARMOURING L.T. PAPER-INSULATED LEAD-COVERED CABLES ; (2) JUTE BRAIDING.

Fig. 161 shows the increase in price of single lead-covered cables when armoured or braided. A jute serving lapped on is much cheaper than jute braiding.

Contracts for the yearly supply of cables are often made dependent on the ruling prices of copper and lead, and the following are examples of the figures.

Cable.	Price per 1,000 yds.
0·1 low-tension single-core	£71. 10s. $\pm$ 11s. . . $x \pm$ 24s. . . y
1·0 low-tension single-core	£552. 15s. $\pm$ 115s. . $x \pm$ 100s . y
0·1 low-tension concentric	£147. 4s. $\pm$ 22s. . $x \pm$ 42s. . y
0·1 high-tension concentric	£161. 0s. $\pm$ 22s. . $x \pm$ 50s. . y

x is the difference in the price of copper above or below £60, expressed in pounds.

y is the difference in the price of lead above or below £12 expressed in pounds.

The figures and formulæ given above are for C.M.A. cables ; German-made cables are often quoted some 10 per cent. lower than these, for large contracts.

The cost of bitumen insulated cables varies with the price of copper , the cost of the insulation varies with different makers to a greater extent than if paper is used. A table of quotation is given below for single low-tension cables, with copper costing £60 per ton —

Section of cable.	Cost per 1,000 yds.	Section of cable.	Cost per 1,000 yds.
0 025	£29	0 25	£173
0 05	45	0 5	312
0 1	78	1 0	573
0·2	135	1 5	850

These prices are from 10 per cent. in small sizes to about 5 per cent. in the larger sizes greater than the corresponding prices of paper lead-covered cables.

Concentric cables cost a very little more than their equivalent single cables—for example, with copper at £57 per ton and lead at £13, a 0 1 concentric cable costs £146 per 1,000 yds., and two 0·1 single cables cost £142 per 1,000 yds., difference = £4 per 1,000 yds , a 0·2 concentric cable costs £260 per 1,000 yds:, and two 0·2 single cables cost £250 per 1,000 yds., difference = £10 per 1,000 yds.

A triple-concentric cable costs slightly less than three equivalent single-core cables', and a three-core cable costs about the same as three singles. If the cables are armoured there is an appreciable advantage by using triple-concentric and three-core cables in preference to single cables.

A three-core pilot cable (conductors 7/22) costs about £35 per 1,000 yds.*

Cost of Aluminium Core Cables.

With low-tension single-core cables and with copper as low as £60 per ton, there is a considerable saving to be made with large section cables by using aluminium in place of copper.

* All the prices given above are only intended to illustrate approximate prices, and must not be considered in any sense as fixed quantities. Prices of small quantities will be higher than those given.

The specific gravity of copper is 8·9 and of aluminium 2·7, and the conductivity of copper relative to aluminium is as 100 to 61.

If x be the price of copper per ton and y the price of aluminium per ton, and z be the cost of any copper conductor, then the cost of an aluminium conductor of equal resistance is

$$\left(z \times \frac{100}{61} \times \frac{2 \cdot 7}{8 \cdot 9} \times \frac{y}{x}\right) = \frac{yz}{2x} \text{ nearly.}$$

But the cost of an insulated cable will not show so much gain as this, because the sectional area is increased in the ratio of 1 : 1·6, and this means a greater amount of insulation and lead. The curve in Fig. 160 cannot be used to calculate the increased

Net saving per mile,

Equivalent Copper Cross Section.
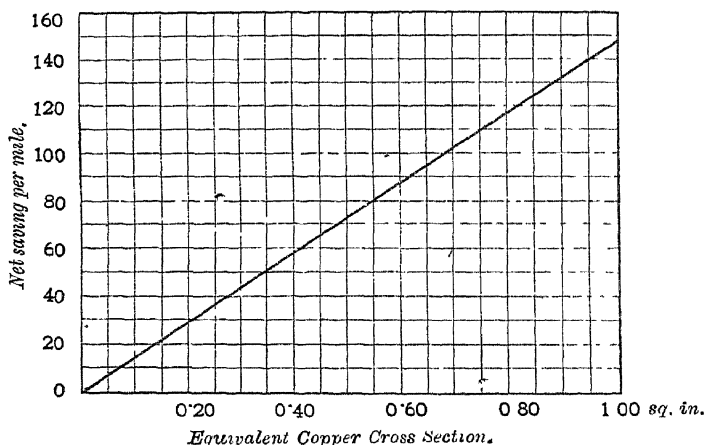
Fig. 162.

charge because it refers to the whole of the costs of the cable, with the exception of the core, and not merely to the bare cost of material. The curve in Fig. 162 is from THE ELECTRICIAN of May 5, 1911, and shows the saving per mile which can be effected by using aluminium cores in place of copper, with raw copper at £60 per ton and aluminium wire at £93⅓ per ton ; it refers to low-tension paper-insulated lead-covered cables, and has been prepared by the British Aluminium Co.

With concentric, multicore and high-tension cables, there is not much advantage to be gained by the use of aluminium, except for extra-high-tension cables of small section, where

aluminium gives a smaller curvature of conductor, so that a decreased thickness of insulation may theoretically be used.

Armoured cables also show no great saving when the conductor is aluminium, for which the principal use is likely to be found in cables of large section transmitting large amounts of power for long distances, and in all cases where bare conductors are used, as in culverts and connections to switchboards and overhead work.

Cost of High-Tension Cables.

The cost of high-tension cables varies more with different makers than those for low tension. The cost of the cores can be worked out as before, and the curves B and C in Fig. 160 (p. 447) will give an approx. price for the rest of the cable, for 2,000-volt concentric and 5,000-volt three-core cables The section in the figure is the section per core, and in the case of the 5,000-volt cable it refers to sector-shaped cores and includes a copper earth sheath. For a rough approximation to the cost of 20,000-volt cables add from £150 to £200 per 1,000 yds. to the cost of a 5,000-volt cable of similar section *

Cost of Laying and Re-instatement of Cables and Services.

The figures given in Table 1. will give some idea of the cost of laying cables , to get the complete cost, of course, that of the cables themselves must be added. The figures include excavating, filling in, laying or drawing in the cables, cartage and everything except jointing and permanent reinstatement of the road surface , they are all obtained from practice, and most of them are averages obtained from a number of different places. The cables used were about 0·25 sq. in. and smaller sections ; for larger sizes of cables the costs would be higher. Again, the labour costs vary enormously with different conditions, depth of track, &c. ; those given above are for fairly easy conditions, such as might be met with in country districts. Cables can be pulled into bitumen casing, which is made in 6 ft. lengths, and consequently has few joints, if laid in

---

* The cost of a 20,000-volt three-core lead-sheathed wire-armoured cable, 0·1 sq. in. section, laid direct jointed and covered with boards, is about 16s. per yard, excluding trench work.

Table I.—*Cost per 1,000 yds.*

Method of laying.	Labour.	Pro-tection.	Total.
Three armoured cables laid direct	£108	... £25	...£133
Three single cables drawn into single 4in. stoneware pipe	100	... 76	... 176
Three ,, ,, ,, 4in. cast-iron pipe	100	... 164	... 264
Three ,, ,, three 2½in. stoneware pipes.	120	... 115	... 235
Three ,, ,, three 2⅜in. wrought-iron pipes .	117	... 111	... 228
Three ,, ,, three 2½ in. stoneware pipes (in concrete)	140	... 143	... 283
Three ,, ,, three 2½in. cast-iron pipes	117	... 237	... 354
Three ,, ,, three-way bitumen casing	100	... 200	... 300
Three ,, ,, three single fibre pipes, with boards	120	... 134	... 254
Three ,, ,, three single fibre pipes in concrete	135	... 153	... 288
Three ,, laid solid in single wood trough	120	... 108	... 228
Three ,, ,, in three-chase stoneware trough	130	... 130	... 260
Three ,, ,, in asphalt troughing	130	... 118	... 248
Triple-concentric or three-core, laid in solid stoneware trough	100	... 100	... 200
,, ,, ,, drawn into 4in. stoneware pipe	90	... 76	... 166
,, ,, ,, ,, 4in cast-iron pipe	100	... 164	... 264
,, ,, ,, ,, 3in. fibre pipe	85	... 95	... 180
,, ,, ,, armoured and laid direct	75	... 25	... 100
Two-pole concentric laid solid in stoneware trough	95	... 75	... 170
,, ,, drawn into stoneware pipe	88	... 60	... 148
,, ,, fibre pipe	85	... 80	... 165
,, ,, armoured and laid direct	75	... 20	... 95

Table II.*—*Cost of Permanent Reinstatement.*

{ Relaying flagstone pavement, contract price	1½d. to 2d. per sq. ft.	
{ Actual cost of relaying .. ..per yard run about	1s.	
Granolithic paving....................	,, ,,	2s.
Macadam road	,, ,,	1d. to 3d.
Stone causeway	,, ,,	1s.
Wood paving	,, ,,	8s.
Gravel footpath	,, ,,	1d.
Asphalt	,, ,,	5s. 6d.

Table III.—*Cost of Connecting Services.*

	£	Q	
7/16 concentric armoured, with board	£0	2	6
7/16 ,, laid solid	0	3	3
7/16 ,, drawn in galvanised iron pipe	0	3	0
Two single 7/16 cables armoured with board	0	3	0
Two ,, ,, laid solid	0	4	0
Two ,, ,, drawn into separate pipes	0	3	6
		K	
Teed-off triple-concentric armoured	£1	4	6
,, ,, solid	1	5	6
,, ,, drawn in	2	5	0
,, single cables laid solid	1	5	0
,, ,, drawn in	2	0	0
,, ,, armoured	1	4	0

* These figures, of course, vary with the locality.

a gravel footpath, or under flagstones, for as little as 1s. per yard run, but 2s. 6d. per yard run is the usual figure taken for estimating. The cost of laying cables " solid " is always increased by bad weather. The figures given in the table for armoured cables include a board for protection.

Table II. gives some approximate costs of reinstatement. If the cables are to be laid under flagstones, it is better to employ a mason to relay them, if the stones are big, rather than to have them relaid by contract at so much per square foot. The figures given " per yard run " are for laying three ways or three cables ; concentric or multicore cables will, of course, work out more cheaply, in some cases.

The cost of house services may be divided into two parts, one part, K, independent of the length of the service, and a part, Q, dependent on its length. Thus the cost of a service is $K+Ql$, where l is the length in yards from joint to fuse boxes. K include fuse boxes, but not a meter. The values given in Table III. are for easy conditions, such as villas ; average values will be higher, as all sorts of difficulties may be met with when getting into old buildings, churches, offices, banks, &c.

APPENDIX A.

ENGINEERING STANDARDS COMMITTEE REPORT ON STANDARD TABLES FOR COPPER CONDUCTORS AND THICKNESSES OF DIELECTRIC.

This Report is published annually in full in " The Electrician " Electrical Trades' Directory and Handbook. An abstract of the conditions chiefly affecting underground cables is given here for easy reference :—

Particulars as to copper conductors will be found in Chap. I., Part II.

The accompanying Table IV. gives some particulars of cables for working pressures up to 660 volts, insulated with paper or jute and lead-sheathed.

The thickness of dielectric and lead for intermediate sizes of conductors, can easily be approximated to, from a consideration of those in the table. Conductors smaller than 0 025 are to have the same thicknesses as given for 0 025.

Table V. refers to concentric cables for various working pressures. The outer conductor is supposed to be earthed, and the cables are paper-insulated.

Table VI. deals with three-core cables for different pressures, with paper insulation. All thicknesses of dielectric and lead are given in inches.

Table VII. below shows the standard testing pressures to be applied. Pressure may be either alternating or continuous current :—

Table VII.

Working pressure.	Pressure test at works.		Pressure test when laid and jointed.	
Up t 660 volts (paper cables)	2,500 v. for ½ hour		1,000 v. for ½ hour	
,, ,, (jute cables)	1,500 ,, ,,		1,000 ,, ,,
2.200v. (concentric or 3-core)	10,000 ,, ,,		4,000 ,, ,,
3,300 ,, ,,	12,000 ,, ,,		6,000 ,, ,,
6,600 ,, ,,	20,000 ,, ,,		12,000 ,, ,,
11,000 ,, ,,	30,000 ,, ,,		20,000 ,, ,,

Table IV.—*Low Pressure Cables.*

Nominal area of conductors in sq. in.	Weight in lb. per 1,000 yds. (min.allowable) single conductor	Resist. in ohms per 1,000 yds. at 15·6°C. (max.allowable) single conductor	Single.		Concentric.		Triple concentric.		Three-core.	
			Thickness of dielectric.	Thickness of lead.	Thickness of dielectric.	Thickness of lead.	Thickness of dielectric.	Thickness of lead.	Thickness of dielectric.	Thickness of lead.
0·025	293	0·981	0 08	0·06	0·08	0 07	0·08	0·08	0·09	0·08
0·05	572	0·5027	0·08	0·06	0·08	0·08	0·08	0·09	0·09	0·09
0·10	1,158	0·249	0·09	0·07	0·09	0·09	0 09	0·10	0·10	0·10
0·20	2,257	0·128	0 09	0 08	0·09	0·10	0 09	0·12	0·10	0·12
0·25	2,842	0·1016	0·10	0·09	0 10	0·11	0·10	0·13	0·11	0·13
0·30	3,424	0·0843	0·10	0·09	0·10	0·11	0·10	0·13	0·11	0·13
0·50	5,647	0·0512	0·10	0·10	0·10	0·13	0 10	0·15	0·11	0·15
0·75	8,425	0·0343	0·11	0·11	0 11	0·14	...	...	...	...
1·00	11,500	0 0251	0·13	0·12	0 13	0·15	..	...	...	...

NOTE.—For concentric cables the inner and outer dielectric thickness is the same, and for triple concentric the inner, intermediate and outer dielectric are all the same thickness. The dielectric thickness given for three-core cables is the same between conductors and from conductors to lead.

Table V.—*Concentric Cables for High Pressures.*

Nominal area of conductors in sq. in.	2,200 volts.			3,300 volts.			6,600 volts			11,000 volts.		
	Dielectric.		Lead.	Dielectric.		Lead.	Dielectric.		Lead.	Dielectric.		Lead.
	Inner.	Outer.		Inner.	Outer.		Inner.	Outer.		Inner.	Outer.	
0 025	0·12	0·08	0·08	0·15	0·09	0·09	0·23	0·10	0·10	0·35	0·12	0·12
0·05	0 12	0·08	0·09	0 15	0·09	0·10	0·23	0·10	0·11	0·35	0·12	0·13
0·10	0·13	0·09	0·10	0·16	0·10	0·10	0·24	0·11	0·12	0·36	0·12	0·14
0·15	0·13	0·09	0·11	0·16	0·11	0·11	0·24	0·12	0·13	0·36	0·12	0·15
0 25	0·14	0·10	0·12	0 17	0 11	0·13	0·25	0·12	0·14	0·37	0·12	0·16

Table VI.—*Three-core Cables for High Pressures.*

Nominal area of conductors in sq. in.	2,200 volts.			6,600 volts			11,000 volts.		
	Dielectric between and outside.	Dielectric outer on star winding with centre earthed.	Lead.	Dielectric between and outside.	Dielectric outer on star winding with centre earthed.	Lead.	Dielectric between and outside.	Dielectric outer on star winding with centre earthed.	Lead.
0·025	0·13	0·10	0·08	0·23	0·17	0·10	0·35	0·23	0·12
0·05	0·13	0·10	0·09	0·23	0·17	0·11	0·35	0·23	0·13
0·10	0·14	0·11	0·11	0·24	0·18	0·12	0 36	0·24	0·14
0·15	0·14	0·11	0·12	0·24	0·18	0·13	0·36	0·24	0·15
0·25	0·15	0·12	0·13	0·25	0·19	0·15	0·37	0·25	0·17

APPENDIX B.

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METHODS OF TESTING.

The Dielectric Strength of Oils and Jointing Compounds.

This test is made with spheres, a convenient size being $\frac{1}{2}$ in. or $\frac{3}{4}$ in. diameter. The spheres may be of brass, and are conveniently carried on brass rods, which are themselves mounted on a piece of ebonite. The whole of the rods must be immersed in the oil to be tested ; the ebonite should be of a convenient length so as to rest on the rim of the vessel containing the oil (a jampot is a suitable vessel). The rods should be of such a length as to bring the spheres not less than 2 in. from the bottom of the vessel. When testing, the pot should be brim full, so as to bring the oil in contact with the ebonite ; the terminals of the brass rods should be sunk in the ebonite and connected to insulated flexible leads, the holes being filled with paraffin. These precautions are necessary to prevent sparking through the air, before sparking through the oil between the spheres. The electrodes should not be less than 0·3 cm. apart ; the width between them should be measured by a brass distance piece, filed down to the required thickness. The experimenter will easily devise a means of holding the rods the proper distance apart, by means of an insulating separator ; it should be well above the spheres. To make a test the spheres are immersed in the oil, and the terminals connected to the testing transformer, and the voltage raised until a spark passes between the spheres. A spark generally passes before the actual breakdown arc takes place. With a translucent oil in a glass vessel this first spark can be seen ; but in this and other cases a small " click " can be heard, if the ear be placed within a few feet of the testing vessel. The voltage at which this occurs is,

noted, and the dielectric strength may then be calculated from the following formula :—

$$R = r \cdot \frac{V}{x} \cdot f,$$

where R = dielectric strength, r = amplitude factor, V = voltage (R.M.S.) at which spark-over occurs, and f is a factor depending on the radius of the spheres, and their distance apart $= x$. r for a sine wave is $\sqrt{2}$. The value of f may be found from the following table, which is taken from Dr. Russell's Paper in " Jour." of I.E.E., Vol. XL., p 9. These values of f are for use when both terminals of the transformer are insulated from earth* ; a is the radius of the spheres :—

Values of f.

x/a.	f	x/a.	f.
0	1	...	...
0·1	1·034	2	1·77
0·2	1·068	3	2·214
0·3	1·102	4	2·677
0 4	1·137	5	3·151
0·5	1·173	6	3·632
0·6	1·208	7	4·117
0·7	1·245	8	4·604
0 8	1·283	9	5 095
0·9	1·321	10	5·586
1·0	1·359	100	50·51
1·5	1·559	...	...

It is important that the oil be freed from moisture before it is tested. This may be done by heating it to 100°C. for 10 minutes and sealing the receptacle whilst it is cooling. It is recommended in Dr. Russell's Paper (*v.s.*) that the oil be dried by allowing hot air to bubble through it. It is important to ascertain the exact temperature, particularly when testing joint-box compounds, as their dielectric strength decreases quickly with increase of temperature, up to the melting point. It is also of the utmost importance that the spheres be properly cleaned before each test ; all traces of any oil from a previous test must be wiped off, as there is evidence which tends to show that a considerable part of the resistance to puncture resides on the surface of the spheres—a kind of skin effect.

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* Values of f, when one pole is earthed, are given in Dr. Russell's Paper. x and a are both measured in centimetres.

The difficulty that is experienced by most supply authorities in testing jointing compounds lies in the lack of a high-voltage transformer, as the spark-over R.M.S. value across a 0·3 cm. gap of a good compound is of the order 20-40 kv., when cold. This difficulty may be partly overcome by connecting transformers in series and testing the compounds at some fixed temperature higher than normal, at which the spark-over voltage comes within the range of the available transformers. All that is then wanted is a standard to compare the results with, and this may be obtained from any first-class firm.

Breakdown Tests on Cables.

These are made both between conductors and between conductors and sheathing A test to destruction such as this cannot, of course, be made on a long length of cable, and it is, in fact, always carried out on a short piece. It is often said that the result is no criterion as to the strength of a long length of cable The only reason we have ever heard for this criticism is that there is a greatly increased chance of weak places in the long length Now we think cable makers, at any rate, would deny the existence of weak places in cables which had passed their factory tests, and if the object of the test be to find the ultimate strength of the normal cable, the "weak place" argument applies in the reverse sense, for if there be less chance of a weak place in a short length, obviously the object of the test is more likely to be attained than by testing a long length, in which by hypothesis there is a greater probability of a weak place. The factory high-pressure test, which must be distinguished from a "breakdown" test, is designed to find any weak places which may exist. With the high pressure test, of course, the whole of the cable is tested. It ought to be recognised that it is equally the interest of the cable maker, as of the buyer, to see that cables with weak places do not leave the factory.

The cable then is connected to the transformer and the voltage raised steadily by a choker or other means. It has been maintained that the voltage must be raised by equal steps in equal intervals of time. This is undoubtedly desirable, but we think it can be sufficient'y approximated to by means of hand regulation, using any method that will increase the pressure gradually. In justification of this it may be said that

results obtained are found to lie on a smooth curve when plotted. As the voltage is increased it will be found that sparking occurs over the surface of the insulation between the lead sheathing and the conductors, or between conductors. We do not think that this sparking affects the result of the test, as we have obtained the same result when the sparking has been completely prevented, as when it has been allowed to take place. It may be prevented by placing cone-shaped paper sleeves filled with compound tied on at the junctions of the insulation and copper and the insulation and lead. When breaking down, say, a 20,000-volt cable, the sparking becomes very severe and very noisy. If an electrostatic voltmeter is used, connected across the cable, the breakdown voltage is indicated by the voltmeter needle dropping back to zero. It is necessary to watch the voltmeter attentively whilst the pressure is being raised, in order to catch the reading at which the needle drops back. One object of making the breakdown test is to get the factor of safety of the cable, which is the breakdown voltage divided by the working voltage. Using British standard thicknesses of insulation, the factor of safety for E.H.T. cables varies from 10 to 20.

Measurement of Dielectric Coefficient.

For a low-frequency measurement we like to use Maxwell's method with the following modification : Instead of calculating the capacity from the resistances and the speed of the rotating commutator, we arrange an adjustable standard air condenser, so that by means of a two-pole two-way switch it may be thrown into the circuit in place of the condenser under test. Then the unknown capacity is first put in circuit, and the resistances and frequency adjusted to get a balance; this being obtained, the standard condenser is substituted by means of the switch, the speed and resistances being kept the same ; the condenser is now varied until a balance is again obtained. The reading of the standard is then the capacity of the condenser under test. When the two capacities are carefully balanced, the switch may be thrown over either way, without deflecting the light spot ; this makes certain that the speed has not altered. The method obviates measuring the speed, and is direct reading. If the substance of which the dielectric coefficient is required is a liquid or a box

compound, a condenser may be made up of two plates about 1 in. in diameter supported on platinum wires fused into glass tubes, down which the connecting wires are passed, making contact with the platinum by means of a little mercury. The plates are held parallel a few millimetres apart by means of a glass cross-piece burnt on the two tubes. To make up a condenser for measuring paper, tape, or other jointing material, tinfoil is generally used. It may be due to a lack of expertness in making up the condensers with tinfoil, but we have always failed to get consistent results with this material, and we much prefer to use two thick steel plates, machine faced, between which a single layer of the material to be tested is placed, and the whole held together with a clamp (insulated from the plates). This makes, of course, a condenser of very small capacity, but there is no difficulty in measuring it, if a standard condenser calibrated in micro-microfarads be used, and consistent results may be obtained.

The capacity having been measured the dielectric coefficient is then calculated from the dimensions of the apparatus as below* :—

$$\text{Dielectric coefficient} = r = \frac{36 \times 10^5 \times \pi}{\dfrac{A}{t}} \times C \text{ mfd.}$$

A = area of plate in square centimetres.

t = thickness of dielectric in centimetres.

C = capacity in microfarads.

The material to be tested must be carefully dried before the test, otherwise the result will be entirely fallacious.

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* *See* " Jour." I.E.E., Vol. XLIX., Fleming and Dyke. This formula " cannot claim extreme accuracy." It is, however, accurate enough for practical purposes, when relative rather than absolute values are generally wanted. Greater accuracy may be obtained by calibrating the apparatus, with oils, or other liquids, of which the dielectric coefficient is accurately known.

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